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AIRCRAFT NOISE EFFECTS ON CULTURAL RESOURCES: ANNOTATED BIBLIOGRAPHY

Carl E. Hanson, Nancy Peterson

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

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FOREWORD

This report is the third 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 summarizing the available literature on aircraft noise-induced vibration of structures, with a focus on damage to historical and cultural resources.

2. 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.

Several of the annotations were written by HMMH, others were taken in whole or in part form abstracts written by the authors of the references cited. We would like to acknowledge the use of these abstracts. Each annotation includes an indication of its source in brackets next to the title.

AIRCRAFT NOISE EFFECTS ON CULTURAL RESOURCES: ANNOTATED BIBLIOGRAPHY

Anon., Assessing Noise Impacts of Air Force Operation -- Guidelines. US Air Force, n.d. [HMMH]

This document provides the planner with limited assistance in assessing the environmental effects of aircraft operations. It assumes that the only property damage which may occur is glass breakage. Furthermore, it provides generalizations which assume that all MOAs have the same distributions of window types, sizes and strengths.

Battis, J. C. Effects of Low Flying Aircraft On Archaeological Structures. Hanscom AFB, MA : Air Force Geophysics Laboratory, 1988. [HMMH]

Induced vibrations from aircraft overflights were measured at Long House, an Anasazi Indian site dating from approximately AD 1300. Aircraft overflights were performed by various fighter and bomber aircraft at altitudes ranging from 60 to over 300 meters (200 to over 1000 feet) above ground level. Seismometers on the Long House structure recorded the vibration response of the ruin. None of the overflights produced responses exceeding established criteria for archaeological sites, taken to be a peak vector sum wall velocity of 1.3 mm/sec (.05 in/sec). A method for determining the admittance functions for archaeological sites using a shotgun firing as acoustic source was tested, but found not useful for large, massive walls. The study concludes that (1) low overflights can induce measurable vibrations in these ancient structures; (2) the motions result from the direct pressure loads on the structure; and (3) the overflight induced motions do not constitute an appreciable threat to the sites.

Battis, J. C. Forecasting Hush House Induced Vibro-Acoustics. In NATO CCMS-Conference On Aircraft Noise In a Modern Society. Number 161, Mittenwald, Germany, 1986. pp. D45-D56. [HMMH]

This report provides an approach for relating sound pressures to vibrations of structures exposed to low frequency sound. The sound source is a jet aircraft engine in a special testing facility called a "hush house" which effectively muffles the audible sound. A hush house allows jet engines to be tested much closer to other aircraft maintenance facilities, but there have been some problems of excessive vibrations of nearby buildings due to infrasonic (very low frequency) emissions. To minimize the potential impact of infrasonic emissions, a procedure was developed to simulate the vibro-acoustic environment in existing structures due to Hush House emissions. Using a mathematical representation, it is possible to derive a mapping of the measured vibro-acoustic response of a structure to a test source, such as an elevated explosion, into a forecast of the environment induced by Hush House emissions. Early results indicate that this technique provides an excellent forecast of the vibro-acoustic environment induced by a Hush House. At Luke AFB, Arizona, 90% of the induced noise and vibration energy was modeled by this technique. The procedure has potential application with many classes of acoustic sources.

Battis, J. C. Hush house Induced Vibrations at the Arkansas Air National Guard Facility, Fort Smith Arkansas. Hanscom Air Force Base, MA : Air Force Geophysics Laboratory, 1987. [Author]

A T-10 jet engine ground run-up noise suppressor, or Hush House, was designed to reduce the audible effects of jet engine testing on the surrounding community. At least in part, the noise suppression characteristics of the Hush House are achieved by the transfer of energy from the audible (> 20 Hz) to the infrasonic range (< 20 Hz). This report describes a case study on a problem where low frequency emissions have had deleterious effects on the vibro-acoustic environment of nearby buildings. The existing siting criteria for the Hush House are inadequate: in one case being too stringent and in another case too lax. An acoustic emissions model for the Hush House is proposed based on multiple jet type sources.

Battis, J. C. Seismo-Acoustic Effects of Sonic Booms on Archaeological Sites, Valentine Military Operations Area. Hanscom Air Force Base, MA : Air Force Geophysics Laboratory, 1983. [HMMH]

Seismo-acoustic recordings of sonic booms were made at two sites in the Valentine Military Operations Area (MOA). Each location was selected as representative of a class of significant archaeological sites found within the MOA. These studies indicate that sonic booms are unlikely to cause damage to the archaeological finds. The expected motions are, at worst, 8 percent of the limits set by strict blasting codes and comparable to velocities that could be produced by local earthquakes which have occurred in the Valentine area. At these levels of motion, competent rock will be unaffected by the transmission of seismic waves. The predicted velocity levels from sonic booms are unlikely to initiate either fracture or spalling in rocks. However, it is possible that in rocks where natural meteorological action has initiated these erosive mechanisms the sonic boom induced motion could accelerate the processes to some small, and probably insignificant, degree.

Battis, J. C. STS Launch-Induced Vibration Forecasts For Vandenberg AFB. Hanscom Air Force Base, MA : Air Force Geophysics Laboratory, 1985. [HMMH]

This report presents a method for launch noise-induced vibration environment forecasts for locations in major structures at the Vandenberg AFB Shuttle launch facility. Forecasts were made by coupling a model for the Shuttle rocket acoustics with observed vibrations of structures due to charge detonations over the launch mount. Vibration criteria, or levels of concern were established for this study. Various locations were assessed for excessive vibrations according to the criteria.

Brentner, K. NASA Langley Research Center, private conversation, April 1991. [HMMH]

This discussion covered a number of topics related to helicopter noise including thickness, loading and blade/vortex interaction noise generation mechanisms, computer based noise prediction models (WOPWOP & ROTONET) and the availability of empirical data.

Brown, R. and Sutherland, L. C. "Measurement and Assessment of Potential Damage to Unconventional Structures from Sonic Booms in an Air Combat Training Area." J. Acoust. Soc. Am., vol.88, Suppl.1, Fall 1990, Paper 4NS2. [HMMH]

This paper describes an experimental program involving measurements of the sonic boom loading and structural response of two unconventional structures. It also includes a brief review of supporting analytical models for the excitation, response and potential damage to the structures. The specific structures investigated consisted of two old adobe buildings at the White Sands Missile range, one being the site of assembly of the Trinity atomic bomb trigger. For these special structures, the measurement procedures required special mounting techniques for the wall response transducers to avoid the use of conventional techniques which could damage the wall surface. The data acquisition system employed real-time digital data recording techniques including an unmanned computer system activated by an acoustic trigger signal from sonic booms.

Brumbaugh, D. S. <u>A Report On the Analysis of the Effect of Helicopter Vibrations on the Pt. Sublime Anasazi Site, Grand Canyon National Park</u>. Flagstaff, AZ : NAU Department of Geology, 1985. [HMMH]

This study looked at the possible short-term damage which might be caused by tour helicopter passbys at the Pt. Sublime Anasazi site. The author concluded from his measurements that for a single tour helicopter, under even the most extreme circumstances, damage will not result to the ruins at the site due to either excessive ground velocity or resonant shaking of the walls. A further conclusion was that no modifications to the present pattern and approach distances of tour helicopters were needed. Long term effects were not studied.

Unfortunately, this research raises more questions than it answers. The measurements described in this report were made with inappropriate instrumentation to determine the potential effects of noise-induced vibration. A seismograph was used along with a seismometer mounted on the ground. This set of instruments produces a paper tape with traces of overall vibration time history. However, it is all but impossible to obtain accurate information about the frequency spectrum of the signal from time history traces. Furthermore, no sound pressure spectra from the helicopter noise were determined. A "helicopter amplitude spectrum" is shown, presumably calculated at discrete frequencies from the time history tracings of the ground velocity signals.

A curious result is that no energy is indicated below 30 Hz, where the maximum sound energy from the main rotor occurs. It is unclear whether the seismometer mounted on the ground was picking up response of the wall or some integrated effect of the wall and the ground. To add to the confusion, the wall natural frequency was determined to be in the 18 Hz to 22 Hz range, a frequency range where there should be significant sound energy from a helicopter. This research needs to be repeated using equipment that can simultaneously measure sound pressure and wall vibrations in a form that can be turned into an admittance function.

Clarkson, B. L. and Mayes, W. H. "Sonic-Boom Induced Building Structure Responses Including Damage." J. Acoust. Soc. Am., vol. 51, no.2, pt.3, Feb. 1972, pp. 742-757. [HMMH]

Although this paper was published twenty years ago, it remains an excellent summary of concepts of sonic boom pressure loading of building structures and the associated responses. The significance of sonic-boom load time histories, including waveshape effects, are illustrated with the aid of simple structural elements such as beams and plates. Also included are discussions of the significance of such other phenomena as three dimensional loading effects, air cavity coupling, multimodal responses, and structural nonlinearities. Sonic boom pressure waves are shown to induce greater wall stresses than those from explosive charges; the push/pull of the positive and negative peaks associated with sonic booms have greater effect than the single peak of the blast signal. Measured reflections, accelerations, and strain data from laboratory models and full-scale building tests are summarized, and compared with predicted values. Damage complaint and claim experience due both to controlled and uncontrolled supersonic flights over communities are summarized with particular reference to residential, commercial, and historic buildings. In particular, cracks in plaster were cited as the leading damage complaint from supersonic overflights. Sonic-boom induced building responses are compared with those from other impulsive loadings due to natural and cultural events and from laboratory simulation tests. Among the historical buildings of interest are cathedrals in Europe where responses of ceiling vaulting and windows to sonic booms, subsonic aircraft, traffic and church activities are reported.

Clifton, J. R.; Brown, P. W. and Robbins, C. R. Methods For Characterizing Adobe Building Materials. Washington, DC : National Bureau of Standards, 1978. [HMMH]

This report was reviewed because of the importance of adobe in vibration sensitive buildings of the Southwest. Methods are described for the characterization of those physical properties and mineralogical features of adobe which appear to have the most significant effect on the durabilities of adobes. These methods include determinations of color, pH, soluble salts, particle size distribution, liquid and plastic limits, and the X-ray "fingerprint" of adobe. In addition, methods are given for the identification of the mineralogy of adobe soils and for the examination of the microfabric of adobe.

Committee on Bioacoustics and Biomechanics (CHABA). Working Group Number 69. Guidelines for Preparing Environmental Impact Statements on Noise. Washington, DC : National Academy of Sciences, 1977. [HMMH]

Proposed guidelines in this report are the result of deliberations of CHABA Working Group 69 over the time period of 1972-1976 and were originally meant for the preparation of Environmental Impact Statements that deal with noise and vibration. Specific impact assessment/quantification methods are presented, along with criteria for damage in structures by vibrations.

Crowley, F. A. Acoustic Forecast For Shuttle Launches at Vandenberg AFB. Weston, MA : Weston Observatory / Boston College, 1985. [Author]

This report provides an indication of the upper range of aircraft noise sources. Acoustic loads on ground support structures for Shuttle launches at Vandenberg AFB are forecasted. Acoustic spectra at points neighboring the Vandenberg Launch Mount are expected to be enhanced by as much as 15 db by site specific features. Simulated launch loads on east face of the Payload Preparation Room have a maximum overall sound power level of 156 db. The corresponding sound power maximum for the same averaging time, bandwidth and distance at Kennedy Space Center over a path free of reverberations and ground water cloud attenuation is 149 db. The peak pressure on the Payload Preparation Room after 10 launches is predicted to be 165 db.

After a lifetime of 100 launches, peak pressure on the facility is expected to reach 167 db. These sound pressure levels are clearly above any that are commonly experienced from aircraft overflights.

Haber, J. M. and Nakaki, D. Sonic Boom Damage To Conventional Structures. Canoga Park, CA : BBN Systems and Technologies Corporation, 1989. (BBN Report 6829) [Author]

United States Air Force supersonic aircraft operations generate sonic booms which may effect existing structures. Typical effects of the sonic boom range from a mild nuisance to damage to windows, plaster and bric-a-brac. A literature survey was performed to identify existing models, suitable for the environmental planner to use for assessing the impact of supersonic flights on conventional structures. A model developed by Hershey and Higgins was identified as the most nearly suitable model. As a result of an extensive sensitivity analysis of this model, a number of enhancements to the model were developed. Finally, the revised model was "packaged" to facilitate use by an environmental planner. A comparison of the existing U.S. Air Force methodology and the mean damage estimates produced by the new approach shows that the existing method usually produces higher loss estimates, although sometimes the loss estimates are comparable. The new method offers the advantage of quantifying the degree of conservatism in damage estimates and extending it from window panes to include other vulnerable materials.

Hershey, R. L. and Higgins, T. H. Statistical Model of Sonic Boom Structural Damage. Bethesda, MD : Booz, Allen Applied Research, 1976. [Author]

The probabilities of structural damage from sonic booms were estimated for various susceptible structural elements using a statistical modeling technique. The breakage possibilities were found to vary widely with the specific material configuration, but to consistently increase with increasing nominal overpressures. The ranges of breakage probabilities at a nominal overpressure of 1 psf for typical configurations of susceptible materials tend to agree well with sonic boom claim experience. This report is the basis for BBN's model for sonic boom damage described in the Haber and Nakaki report.

Hubard, H. H. " Noise Induced House Vibrations and Human Perception." ***Noise Control Eng.*****, v.19, no. 2, Sept.-Oct. 1982, pp.49-55. [HMMH]**

This paper summarizes noise induced house responses including frequencies, mode shapes, acceleration levels and outside-to-inside noise reductions. The role of house vibrations in reactions to environmental noise is defined and some human perception criteria are reviewed.

King, K. W. "Helicopter Pressure Loadings on Buildings with Viga Construction, Mesa Verde." Report in Progress, 1991. [HMMH]

Kenneth King of the U.S. Geological Survey measured vibrations on the flat roof of an adobe building with flat roof of an adobe building with flat roof and viga construction while a small helicopter hovered nearby. He found the greatest roof response to occur at 13 Hz with the second highest peak at 27 Hz. These frequencies corresponded to first and second harmonies of the main rotor. Concern was expressed for the possibility of excessive corner stresses and for cracking in the vicinity of the Viga supports. Although he did not measure sound pressure from the helicopter, he found greater roof vibration when the helicopter hovered off to one side than when overhead.

King, K. W. and Carver, D. "Measurements of Wall Vibrations during Ceremonial Dancing at Casa Rinconada, Chaco Canyon." Report in peer review, 1989. [HMMH]

These measurements showed that wall natural frequency of an ancient kiva was about 12 Hz, while vibrations from drum sounds occurred no lower than 18 to 20 Hz. Consequently King concluded there was no risk of damage from ceremonial drumming inside the kiva. Footsteps caused vibrations in the walls at very low frequencies. The author concluded that vibrations from neither the ceremonial dancing nor the site visitors posed a threat to the structures.

King, K. W. "Casa Grande Ruins Vibration Investigation." In Review. Denver, CO : U.S. Geological Survey, 1990. [HMMH]

This investigation dealt with potential damage by vibration from traffic. The researcher demonstrated by experiment that vibrations from traffic in a nearby parking lot could initiate surface cracks in adobe that could admit moisture to the core. He thereby explained the curious erosion of the base of walls at this prehistoric Hokokam site. This case is used as an example of how minute surface cracks from vibration, such as aircraft noise-induced vibration, can set into motion a natural chain of events leading to structural damage.

King, K. W.; Algermissen, S. T. and McDermott, P. J. Seismic and Vibration Hazard Investigations of Chaco Culture National Historical Park. Denver, Co : U.S. Geological Survey, 1985. [Author]

The potential for damage to structures in Chaco Culture National Historical Park resulting from earthquakes, landslides, industrial blasting, road building and vehicular traffic is reported. This Park, located in Northwestern New Mexico, contains over 2,000 known archaeological sites. The structures of interest, many of them multistory and a few containing over 200 rooms, date from the 11th and 12th centuries. Most of the remaining walls are 1.5.to 3.0 m in height, but a number exceed 5.0 m. A 2.0 mm/sec particle velocity is recommended as the upper limit induced motions in the structures resulting from industrial blasting, road building and vehicular traffic. Minimum distances of these activities from the structures are recommended based on field recordings and analysis of the induced vibrations from these sources. Minimum distances of 1.2 km from blasting, 0.5 km from railroad traffic, 45 m from road building and 25 m from vehicular traffic are recommended based on normal blasting practices in the area, conventional rail traffic, usage of road building equipment and normal vehicular traffic patterns. Recommendations are also made for controlling vibrations from one road in the Historical park considered to be too close to historical structures. Levels of expected ground motion from earthquakes, even for a relatively short time periods of interest such as 50 years, indicate that possible future earthquake damage to the structures should be considered. The implication is that at least some of the past deterioration of the structures in the Historical Park may have been caused by earthquake ground motion.

King, K. W. "A Vibration Study of the Archaeological Ruins, Hovenweep National Monument, Utah-Colorado." Denver, CO : U.S. Geological Survey Open File Report 87-181, June 1987. [HMMH]

Criteria for vibrations of prehistoric structures were developed and used in this study. A peak velocity of ground at the base of a structure of 0.004 in/sec over a frequency range of 1 to 10 Hz was determined to be the threshold for avoiding damage.

Konon, W. and Schuring, J. R. "Vibration Criteria for Historical Buildings." ***Journal of Construction Engineering and Management*, v. 111, no. 3, Sept. 1985, pp. 208-215. [HMMH]**

This paper discusses applicable damage criterion for historical buildings subjected to construction-induced ground vibrations. The 2.0 in/sec (50 mm/s) peak particle velocity criterion traditionally used to protect structures from construction-induced vibration damage is not appropriate for historic and sensitive older buildings. Existing criteria by past investigators are reviewed. A new criterion for this class of structure is recommended: A peak particle velocity of 0.25 in/sec for frequencies below 10 and 0.50 in/sec above 40 Hz, with a straight line transition between 0.25 in/sec and 0.50 in/sec for frequencies between 10 Hz and 40 Hz.

Legg, M. R. and Huber, J. M. Seismic Response of Sonic Boom-Coupled Rayleigh Waves. Canoga Park, CA : BBN Systems/ACTA, 1990. [Author]

This study investigated the possibility of seismic waves in the ground being excited by sonic booms. Under most conditions, the energy transfer from air to ground is very inefficient, and the seismic wave energy is dissipated over a relatively short distance. If however, a supersonic aircraft flew in a manner so that the sonic boom carpet velocity matched the propagation velocity of seismic surface waves (Rayleigh waves), the magnitude of the seismic waves would be amplified. For special soil (ground) characteristics, the energy transfer into the ground becomes more efficient. The seismic energy can propagate with little dissipation, allowing the magnitude of the ground vibrations to build up to damaging levels. If the vibration characteristics of the ground match those of the structure, the potential for structural damage may be significant. However, the probability of all these factors occurring at once is very slight.

Mears, A. I. Guidelines and Methods for Detailed Snow Avalanche Hazard Investigations in Colorado. (Bulletin 38) Denver, CO : Colorado Geological Survey, 1976. [HMMH]

The objective of this publication is to provide guidelines for evaluating quantitatively the potential size and destructive force of avalanches in Colorado through indirect methods of analysis. Because avalanche dynamics are imperfectly understood, no clear-cut solutions to problems can be offered. Instead, it is continually emphasized that several different, completely independent methods of analysis should be employed simultaneously, thereby reducing the uncertainty inherent in a single method. No mention of sound-induced avalanches was made.

National Research Council. Panel on Snow Avalanches. Snow Avalanche Hazards and Mitigation in the United States. Washington, D.C. : National Academy Press, 1990. [Author]

This report by the Committee on Ground Failure Hazards Mitigation Research addresses the problems and mitigation issues concerning snow avalanche hazards in the United States. The purpose of this report is to provide national, regional, and local governments; government agencies; and private decision makers with an overview of the snow avalanche situation in the United States and to outline steps that can be taken to minimize domestic avalanche problems. Four major points are emphasized. 1) Support for avalanche programs has diminished alarmingly at a time when increasing numbers of people are using mountain areas for recreation and commercial and other types of development are increasing in formerly remote areas. 2) The incidence of avalanche accidents is increasing and is expected to continue to increase in the future. 3) There is a lack of nationwide coordination, accepted standards, and effective information flow among those involved in avalanche mitigation. 4) There are no standardized procedures for avalanche control and equipment testing. Control techniques and equipment that use explosives have specific standards and problems that must be addressed.

National Technical Information Service. Aircraft Sonic Boom : Effects on Buildings (Jan 70 - Feb 90). Springfield, VA : NTIS, 1990. [Author]

This bibliography contains citations concerning the effects of sonic booms on building structural components, forms, windows and walls. Test-house investigations, damage analysis, and vibration response are included. Other topics included in this published search range from theory to failure analysis. These topics cover overpressures as measured and simulated from various aircraft and space shuttle reentry configurations.

Newman, J. S.; Rickley, E. J.; Bland, T. L. and Daboin, S. A. Noise Measurement Flight Test for (Various) Helicopter: Data and Analysis. Washington, DC : Federal Aviation Administration, 1984. [HMMH]

This series of reports documents the results of a Federal Aviation Administration (FAA) noise measurement flight test program with various helicopters. The reports contain documentary sections describing the acoustical characteristics of the helicopters and provides analyses and discussions addressing topics ranging from acoustical propagation to environmental impact of helicopter noise. There are seven reports documenting the FAA helicopter noise measurement program conducted at Dulles International Airport during the summer of 1983. The test program involved the acquisition of detailed acoustical, position and meteorological data. The program was designed to address a series of objectives including: 1) acquisition of acoustical data for use in assessing heliport environmental impact; 2) documentation of directivity characteristics for static operation of helicopters; 3) establishment of ground-to-ground and air-to-ground acoustical propagation relationships for helicopters; 4) determination of noise event duration influences on energy dose acoustical metrics; 5) examination of the differences between noise measured by a surface mounted microphone and a microphone mounted at height of four feet (1.2 meters); and 6) documentation of noise levels acquired using international helicopter noise certification test procedures. These data were collected for purposes relating to human audition. Therefore the frequency spectrum extends down only to 25 Hz. Thus, the sound from the main rotor fundamental frequency is not included in the data.

Nichols, H. R.; Johnson, C.F. and Duvall, W. I. Blasting Vibrations and Their Effects on Structures. Bulletin 656. Washington, D.C. : Bureau of Mines, USDI, 1971. [Author]

This report presents the results of the Bureau of Mines 10-year program to study the problem of air blast and ground vibrations generated by blasting. The program included an extensive field study of ground vibrations; a consideration of air blast effects; an evaluation of instrumentation to measure vibrations; establishment of damage criteria for residential structures; determination of blasting parameters which grossly affected vibrations; empirical safe blasting limits; and the problem of human response. While values of 2.0 in/sec particle velocity and 0.5 psi air blast overpressure are recommended as safe blasting limits not to be exceeded to preclude damage to residential structures, lower limits are suggested to minimize complaints. Millisecond-delay blasting is shown to reduce vibration levels as compared to instantaneous blasting, and electric cap delay blasts offer a slight reduction in vibration levels as compared to Primacord delay blasts. Vibration levels of different blasts may be compared at common scaled distances, where scaled distance is the distance divided by the square root of the maximum charge weight per delay. Geology, rock type, and direction affect vibration level within limits. Empirically, a safe blasting limit based on a scaled distance of 50 ft/lb may be used without instrumentation. However, a knowledge of the particle velocity propagation characteristics of a blasting site determined from instrumented blasts at that site are recommended to insure that the safe blasting limit of 2.0 in/sec is not exceeded.

Richart, F. E, Jr. and Woods, R. D. Vibrations of Soils and Foundations. Englewood Cliffs, NJ: Prentice Hall, 1970. [HMMH]

This reference book has become a classic in the field of ground vibrations. Explanation of the physics of ground vibration propagation and coupling with building foundations are especially clear. The ground characteristics are found to be important for vibration from surface transportation, but of minimal importance for aircraft noise-induced vibrations.

Schoemer, P. D. and Neathammer, R. The Role of Vibration and Rattle in Human Response to Helicopter Noise. Champaign, IL : U.S. Army Construction Engineering Research Laboratory, 1985. [Author]

The understanding of community reaction to helicopter noise remains incomplete. The standard approach of "A-weighting" measured noise levels appears to produce realistic data outdoors and at modest noise levels, and the community response in terms of percentage of population highly annoyed can be correlated with respect to the Day/Night Average Sound Level (DNL) descriptor. However, questions remain as to the effect of perceived building vibration and rattle on human response to helicopter noise. Does hearing windows, ceiling tiles, or objects in the room rattle or the general perception of building vibration increase the publics adverse response to helicopter noise? To answer these questions this study examined the role of vibration and rattle in human response to helicopter noise. Many volunteer subjects were tested under real noise conditions. The noise was generated by an Army UH-1H (Huey helicopter). Subjects were located either in the living room of a new mobile home, outdoors, or in the living room or dining room of an old frame farmhouse near Champaign, IL. The control or comparison sound was generated electronically through loudspeakers at each location using a 500-Hz octave band of white noise. By performing paired comparison tests between the helicopter and control noises, it was possible to establish equivalency between these two stimuli. Among the recommendations from this study were maintaining a separation distance of 500 feet and preferably 1000 feet between the UH-1 helicopter and residential buildings to avoid significant rattle.

Siskind, D. E.; Stachura, W. J.; Stagg, M. S. and Kopp, J.W. Structure Response and Damage Produced by Airblast From Surface Mining. Report of Investigations 8485. Washington, D.C. : Bureau of Mines, 1980. [Author]

The Bureau of Mines studied airblast from surface mining to assess its damage and annoyance potential, and to determine safe levels and appropriate measurement techniques. Research results obtained from direct measurements of airblast-produced structure responses, damage, and analysis of instrument characteristics were combined with studies of sonic booms and human response to transient overpressures. Safe levels of airblast were found to be 134 dBL (0.1 Hz), 133 dBL (2 Hz), and 105 dB C-slow. These four airblast levels and measurement methods are equivalent in terms of structure response, and any one could be used as safe-level criterion. Of the four methods, only the 0.1-Hz high pass linear method accurately measures the total airblast energy present; however, the other three were found to adequately quantify the structure response and also present techniques that are readily available to the industry. Where a single airblast measuring system must be used, the 2-Hz linear peak response is the best overall compromise. The human response and annoyance problem from airblast is probably caused primarily by wall rattling and the resulting secondary noises. Although these will not entirely be precluded by the recommended levels, they are low enough to preclude damage to residential structures and any possible human injury over the long term.

Siskind, D. E.; Stagg, M. S.; Kopp, J. W. and Dowding, C. H. Structure Response and Damage Produced by Ground Vibration From Surface Mine Blasting. Report of Investigations 8507. Washington, D.C. : Bureau of Mines, 1980. [Author]

The Bureau of Mines studied blast-produced ground vibration from surface mining to assess its damage and annoyance potential, and to determine safe levels and appropriate measurement techniques. Direct measurements were made of ground-vibration-produced structure responses and damage in 76 homes for 219 production blasts. These results were combined with damage data from nine other blasting studies. Safe levels of ground vibration from blasting range from 0.5 to 2.0 in/sec peak particle velocity for residential-type structures. The damage threshold values are functions of the frequencies of the vibration transmitted into the residences and the types of construction. Particularly serious are the low-frequency vibrations that exist in soft foundation materials and/or result from long blast-to-residence distances. These vibrations produce not only structure resonances (4 to 12 Hz for whole structures and 10 to 25 Hz for midwalls) but also excessive levels of displacement and strain. Threshold damage was defined as the occurrence of cosmetic damage; that is, the most superficial interior cracking of the type that develops in all homes independent of blasting. Homes with plastered interior walls are more susceptible to blast-produced cracking than modern gypsum wallboard; the latter are adequately protected by minimum particle velocity 0.75 in/sec for frequencies below 40 Hz. Structure response amplification factors were measured; typical values were 1.5 for structures as a whole (racking) and 4 for midwalls, at their respective resonance frequencies. For blast vibrations above 40 Hz, all amplification factors for frame residential structures were less than unity. The human response and annoyance problem from ground vibration is aggravated by wall rattling, secondary noises, and the presence of airblast. Approximately 5 to 10 percent of the neighbors will judge peak particle velocity levels of 0.5 to 0.75 in/sec as "less than acceptable" (i.e., unacceptable) based on direct reactions to the vibration. Even lower levels cause psychological response problems, and thus social, economic, and public relations factors become critical for continued blasting.

Stagg, M. S.; Siskind, D. E.; Stevens, M. G. and Dowding, C. H. Effects of Repeated Blasting on a Wood-Frame House. Report of Investigations 8896. Washington, D.C. : Bureau of Mines, 1984. [Author]

The Bureau of Mines arranged to have a wood-frame test house built in the path of an advancing surface coal mine so it could investigate the effects of repeated blasting on a residential house. Structural fatigue and damage were assessed over a 2 year period. The house was subjected to vibrations from 587 production blasts with particle velocities from 0.10 to 6.94 in/s. Later, the entire house was shaken mechanically to produce fatigue cracking. Failure strain characteristics of construction materials were evaluated as a basis for comparing strains induced by blasting and shaker loading to those induced by weather and household activities. Cosmetic or hairline cracks 0.01 to 0.10 mm wide occurred during construction of the house and also during periods when no blasts were detonated. The formation of cosmetic cracks increased from 0.3 to 1.0 cracks per week when ground motions exceeded 1.0 in/s. Human activity and changes in temperature and humidity caused strains in walls that were equivalent to those produced by ground motions up to 1.2 in/s. When the entire structure was mechanically shaken, the first crack appeared after 56,000 cycles, the equivalent of 28 years of shaking by blast-generated ground motions of 0.5 in/s twice a day.

Stephens, D. G. and Hayes, W. H. "Aircraft-Induced Building Vibrations", Community Noise. ASTM STP 692. Philadelphia, PA : American Society for Testing Materials, 1979, pp. 183-194. [Author]

Community noise surveys have often identified building vibration as a source of annoyance in airport communities. During the mid 70's concern for building vibration was associated with the introduction of the Concord supersonic transport into the United States because of the relatively high levels of noise. The objective of this paper is to describe a study of building vibration resulting from aircraft and non-aircraft events in the vicinity of Dulles and John F. Kennedy International Airports. The measurement, quantification, and assessment of the noise and the associated vibration of windows, walls, and floors are described for several homes. Results include relationships between aircraft noise and building vibration and between vibration and human response. Comparisons of building vibration data with existing criteria for building damage and human response are also included.

Sutherland, L. C. Assessment of Potential Structural damage From Low-Altititude Subsonic Aircraft. Wyle Report WR-89-16(R). El Segundo, CA : Wyle Research, 1990. [Author]*

This report is a key reference for a study of aircraft noise effects on cultural resources. It presents an analysis of the potential damage effects from acoustic aerodynamic noise generated by military aircraft flying subsonically at low elevations on military training routes (MTRs), but it also applies to noise from civilian aircraft.

Damage potential is estimated on the basis of statistical models for the magnitude peak structural (stress) response to acoustic excitation and corresponding statistical models for the damage (stress) threshold or strength. The result is that the final damage assessment can be given in terms of statistical estimate of the probability of damage as designated by the statistical distribution for the factor of safety - the ratio of structural strength to peak stress response. The report provides, for the first time, a simple empirical model for the low frequency noise from the MTR aircraft of primary concern for structural loads. In addition, the statistical distribution of noise levels from MTR aircraft that would be observed at fixed locations relative to the MTR track centerline is developed. Finally, a comprehensive statistical model is developed to allow systematic estimates to be made of the probability of damage to a wide range of structural types from MTR flights.

Principal findings indicate that a small but finite probability of damage to some structures can be expected for heavy traffic of bomber aircraft on low altitude MTR flights. Similar flights of heavy helicopters at altitudes down to 50 ft. may cause significant damage to structures located close

* Opinion attributable to HMMH.

to their flight tracks. Careful planning of low level flights for such heavy helicopters is indicated to avoid overflights over structures. MTR flight planning for light helicopters, fighter and cargo/transport aircraft must also consider routes to avoid structural damage, even though it is less than those for bombers and heavy helicopters.

Sutherland, L. C.; Brown, R. and Gorner, D. Evaluation of Potential Damage to Unconventional Structures by Sonic Booms. El Segundo, CA : Wyle Laboratories, 1990. [HMMH]

This report is another key reference for the National Park Service study. Supersonic operations of U.S. Air Force aircraft cause sonic booms which may be the source of damage to unconventional structures like those administered by the National Park Service. This problem is addressed in this report by (1) a literature survey of damage prediction and damage assessment techniques for such structures; (2) development of a statistical model for sonic boom overpressures with emphasis on supersonic operating areas employed for air combat maneuver training; (3) development of an analytical model to predict the probability of damage; (4) execution of a limited experimental program at White Sands Missile Range to evaluate response and potential damage of two unconventional structures in support of the prediction model; and finally (5) definition of algorithms for use in the Air Force ASAN computer program for evaluation of the probability of damage to unconventional structures from sonic booms.

Wiggins, J. H. The Effects of Sonic Boom on Structural Behavior - A Supplementary Analysis Report. John Blume & Associates, Final Report, Contract No. FA-SS-65-12, October 1965. [HMMH]

This is one of several reports by this author who was involved in evaluating damage from sonic boom tests at White Sands Missile Range in the early 1960's His reports contain a comprehensive summary of methods to assess whether cracking in structural elements is caused by sonic booms or natural forces. This one outlines the factors which influence the ability to observe and record cracks in structures and provides a method of damage assessment.

Yue, C. and Yue, D. The Pueblo. Boston, MA : Houghton Mifflin, 1986. [HMMH]

This book describes the life of early natives in The American Southwest. It illustrates how the villages were built, including dimensions and construction details of the typical village structures.