INVESTIGATION OF HELICOPTER INDUCED VIBRATIONS AT BALCONY HOUSE, MESA VERDE

by

K.King, 1996

Introduction

During the fall of 1991, a vibration study was conducted at Mesa Verde on the Balcony House, Cedar Tree structure, and the resource building. The study determined the natural frequencies of the structures, the induced vibrations to the structures from vehicle traffic, foot traffic, and low flying helicopters. The helicopter tests documented the effects of a low flying helicopter on a viga supported, flat roof. The test indicated that a viga type roof can amplify the aircraft induced motions by a factor of 12, and these amplified vibrations can be sufficient to cause stress cracks at the viga-wall connections (King, 1991). An unexpected observation made during the roof tests indicated that a very low hovering helicopter off to the side of the building may induce some very high amplitude vibrations that may be of more concern than overhead flights. This observation brought attention to the question of the effects that a helicopter may have while hovering horizontal to a cliff dwelling.

As a result of these preliminary investigations, further evaluations were conducted by testing the explicit effects attributable to helicopter induced vibrations. The Park superintendent, Robert Hyder, was able to schedule the use of a helicopter for a series of 34 vibration tests at the Balcony House in the early morning before the structure was open to the public. This short report presents an abbreviated version of those tests and results.

Helicopters are very complex machines which radiate vibrations that are very complex. Helicopters induce an array of vibrations from several sources (Fig. 1); (a) The tail rotor, (b) the power plant and transmission , and (c) the main rotor . Noise (sound) is a pressure wave in the atmosphere which acts as a force on the structures according to the size of the wave (d). The frequency of the pressure wave from the rotor blades is equal to the revolutions per second times the number of blades of the main rotor. A series of almost pure frequencies are induced from the periodic disturbances of the air by the rotation of the blades.

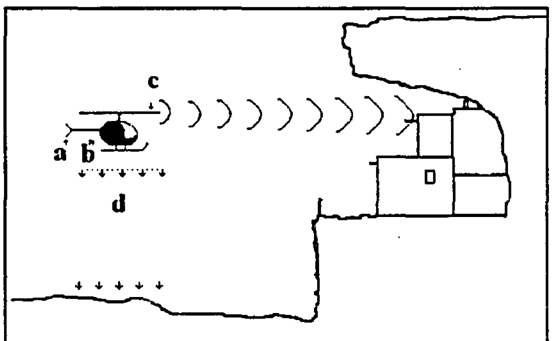

Figure 1

The machinery noise from the transmission and power plant is usually above 200 Hz which is audible and sometimes disturbing to ground personnel but generally above the frequencies of concern to most historic structures (King, 1989). The tail rotor due to its small size and higher speed is usually in the 50 to 150 Hz frequency bandwidth which is also well above the frequencies of concern to historic structures. . The frequencies induced by the main rotor are usually in the 5 to 15 Hz bandwidth with multiples (harmonics) up to 50 Hz. These frequencies are similar to the natural frequencies of many historic buildings.

The main rotor induces a steady pressure pulse on the area at right angles below the blades (Fig 1, d). Other investigations as Sutherland (1990) have shown that this overpressure is very light and though disturbing to people, it is of no threat to structures. Studies at the Cedar

House etc. have shown the same results as obtained by Sutherland; however, the vibrations from a low hovering aircraft are sufficient to cause damage to flat, viga roofs structures such as the resource building. Flybys of the craft (moving rather then hovering) at 100 feet did not induce sufficient vibrations to be a risk to the structures (King, 1991).

A popular concern is with the lift blades is when they emit the "pop", "pop", "pop" sound which occurs when the craft is making a high speed turn or a high speed descent. Tests at the resource building and Cedar House showed no appreciable increase of the lower frequency amplitudes with these overhead maneuvers (King, 1991).

The main rotor induces a second type of pressure wave. Brentner (1991) made an extensive model of the noise envelopes induced by the mechanics of a helicopter. He showed that there should be a second component called "thickness noise" which will progress out horizontally from the tips of the main rotor blades . This "noise" would be in a narrow angular area of about 10 degrees from the plane of the rotating blade. The induced vibrations observed at the resource building from the operation of a helicopter in a position as depicted in figure 1, detail c , may have been "thickness noise".

Operations

A precise 50 foot reference line linear to the Balcony site was established before the helicopter test runs. The vibration recording instruments were located at the west end of the line (position x, Fig. 2) along with a K&E pocket transit mounted on a tripod. A second K&E pocket transit mounted on tripod was located at the east end of the line at location "y". The transits focused on the near, outside rim of the rotating main blades. The "x" transit maintained the craft alinement at 90° while the "y" varied the location from 45° (50 foot range), 63.5° (100 foot range) and 76° (200 foot range).

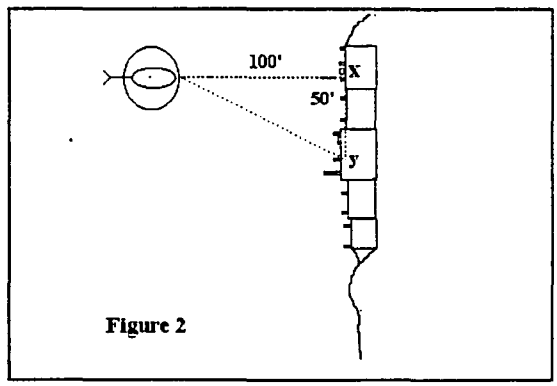

Figure 2

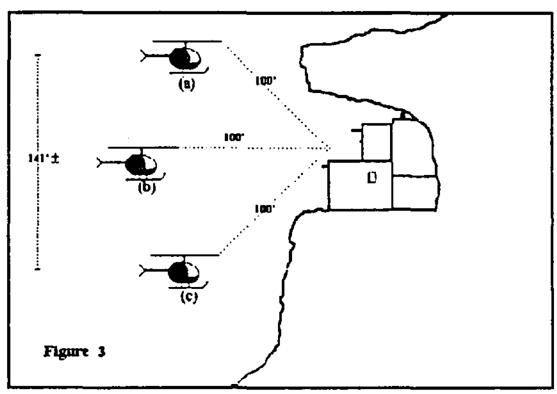

Figure 3

Two sightings with the transits were necessary to establish the range to the craft when it was above and below the horizontal plane (Fig. 3). Safety and time restraints permitted only one series of tests at one range (100 feet) for the above and below horizontal plane locations.

The vibration detection equipment consisted of vibration sensing elements in a tripartite array with the radial horizontal sensing geophone sensitive to motion directly toward and away from the helicopter's position. A second vibration system was located on a 11 foot wall of the structure. A description and calibration of the vibration system are shown in the Chaco Canyon report (King 1985), or Hovenweep report (King, 1987). One system was located on the rock base of the structure and a second system was located on the top of a 11 foot wall.

The helicopter weighs approximately 2,400 pounds and had a 35 foot main rotor blade that turned approximately 390 revolutions per minute during the tests. The small tail rotor was 64 inches in diameter and turned 2,250 rpm during the tests.

Several practice runs were made before the formal tests. . The main test runs comprised of the following: First hovering-series at 200 foot range horizontal to the structures (Fig.3b); Second hovering-series at 100 foot range in the horizontal plane (b); Third series, hovering at a 50 foot range in the horizontal plane (b); Fourth series, hovering at a 200 foot range + 45° to the horizontal plane (a); Fifth series, at a 100 foot range at +45° to the horizontal plane (a); Sixth series, at a 200 foot range below the horizontal plane at a -45° angle (c) ; and, the Seventh series, at a 100 foot range at -45° to the horizontal plane (c).

Once the aircraft was in the proper location, the position was held for approximately 30 to 40 seconds except for the single 50 foot test range. The 50 foot range tests was limited to a shortened duration due to safety and vibration concerns. Preliminary scalings of the documented vibration amplitudes were made after each test run. The test range for the helicopter was reduced only after the data from the present range indicated that the induced motions were below a 2 mm/sec threshold (selected by author as the safe level). The induced motions on the top of the wall momentarily exceeded the 2 mm/sec threshold at the 50 foot test range and the tests were immediately aborted. No other tests were made at the 50 foot range.

The induced vibrations from several helicopter high speed turns and rapid ascents and descents at an approximate 300 foot range were made. None of the vibrations induced by the helicopter on these test approaches and turns exceeded the vibrations induced by the helicopter during hovering tests.

Data and Analysis

Twenty seconds of data were selected from each test for complete data analysis. Each range location had three separate runs except for the 50 foot range. The methods used in this paper for analysis are described in previous reports (King, 1990,1991).

Figures 4, 5, and 6 show the time-histories (real time-graphs of the vibrations) of the recorded, induced vibrations from the helicopter. The time-history graphs have been normalized by setting the same gain to all trances. This gives a relative visual comparison. Figure 4 is a set of recorded vibrations with the helicopter in the same vertical and horizontal plane as the sensors and cliff structures. The top trace (below the time line) shows the vibrations induced in the vertical plane from the helicopter positioned 50 feet from the sensor. The second trace shows the vibrations in the horizontal plane at right angles to a line toward the helicopter (transverse direction). The vibrations would be in a left-right direction when facing the helicopter. The third trace shows the vibrations in the horizontal plane directly toward and away from the helicopter (radial direction). The fourth, fifth, and sixth traces are the induced vibrations (vertical, transverse-horizontal, and radial-horizontal respectively) with the helicopter 100 feet from the sensor. The seventh, eighth and ninth traces are the vertical, transverse and radial vibrations induced by the helicopter at 200 feet from the sensor.

Figure 5 is a similar trace lineup with the helicopter 45° above the horizontal plane of the cliff dwelling. The top three traces are the vertical, transverse horizontal and radial horizontal sensors with the helicopter at a 100 foot range. Traces four, five and six are the same with the helicopter at a 200 foot range. Figure 6 is similar to figure 5 with the helicopter below (-45°) the horizontal plane with the cliff dwelling at a 100 and 200 foot ranges. The amplitudes of Figures 5 and 6 are at the same scale as Figure 4 to allow a visual comparison. Three tests were run at each position (except at the 50 foot range). The scalings at each position were near identical. All fell within a 10% variance.

The spectral analysis show which frequencies are being induced into the structures. The analysis was done over a bandwidth range of 0 to 100 Hz.

The figures on this page show the vibration time-histories that were recorded from the helicopter induced vibrations at various ranges.

Points to note: [1] Figure 4 shows the vertical component amplitudes at all ranges, (traces 1,4, and ,7) are much smaller then the horizontal components amplitudes at the same range; but, [2] figure 6 shows that in the + 45° plane, the vertical vibrations at the 100 foot range tests are nearly equal to the horizontal vibrations; and, in the -45° plane shown on figure 5, the vertical amp-amplitudes are much smaller---very near the ambient background. [3] All figures show that the vertical vibrations have a greater decrease of amplitude (attenuation) with distance then the horizontal vibrations.

Also note; [4] the horizontal vibration amplitudes at the 50 foot range are much larger than any of the other recorded vibration amplitudes;[5] the horizontal vibrations at 100 foot range in the -45° plane (fig. 5) are smaller than the 100 foot range test horizontal vibrations in the 0° plane (fig.4); but they are larger than the horizontal vibrations in the 100 foot +45° plane tests. (fig.6).

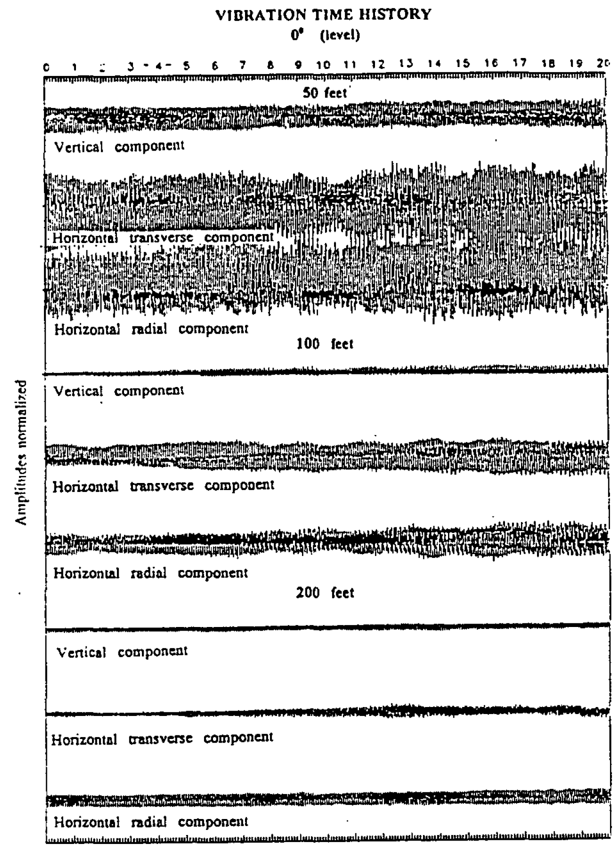

Figure 4

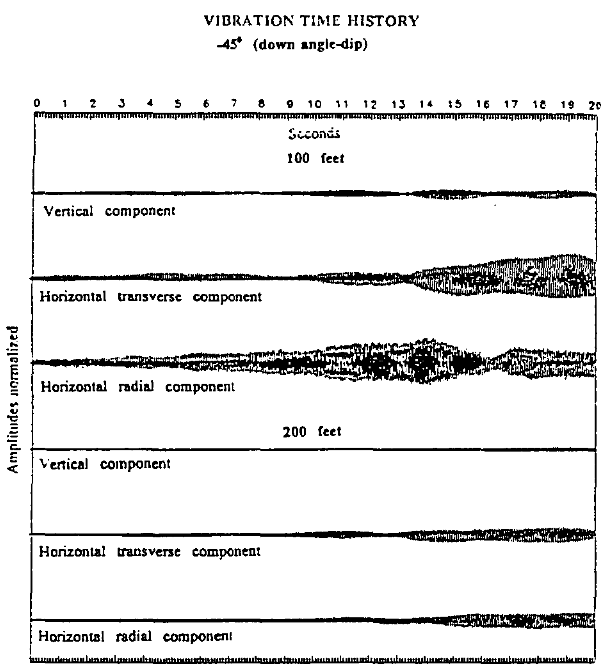

Figure 5

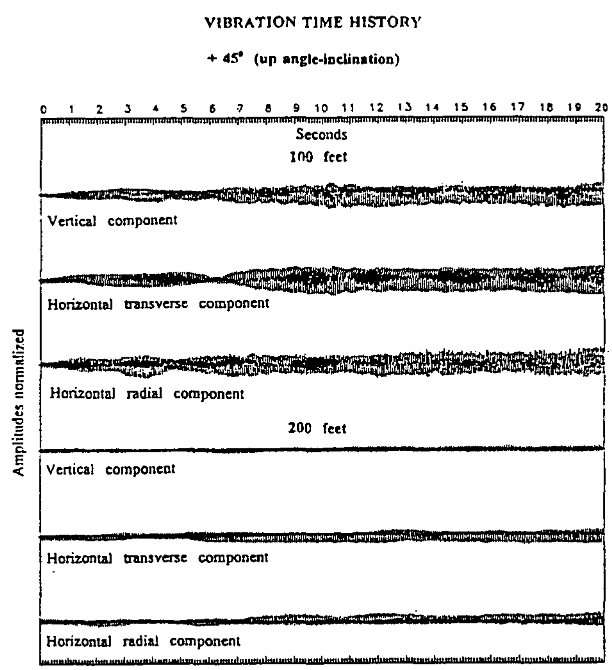

Figure 6

Figure 7 shows the predominate frequencies derived from the 50 foot range horizontal radial time-history shown on figure 4. The spectrum shown on figure 7 indicates a high inducement of almost pure frequencies of 6, 13, 26, 39, 54 and 66 Hz.

Figure 9 is spectrum derived from the data shown on figure 4 at the 100 foot range. The spectra of this data show a moderate amount of attenuation. The spectra peaks remain pure at similar frequencies derived from the 50 foot range data (13, 26, and 40 Hz).

Figure 8, spectra derived from the horizontal vibration data shown on figure 6, indicates considerable attenuation from the 0° data and less pure spectra peaks. The general peaks are similar to figures 7 and 9.

Figure 10 shows the spectra derived from the horizontal vibration data shown on figure 5. This spectra indicates considerable attenuation (lower levels) of the general frequency bandwidth; however the peaks are cleaner (more pure) then the + 45° data and the 13, 26, and 40 Hz peaks are of a greater amplitude then similar frequencies derived from the + 45° 100 foot helicopter test.

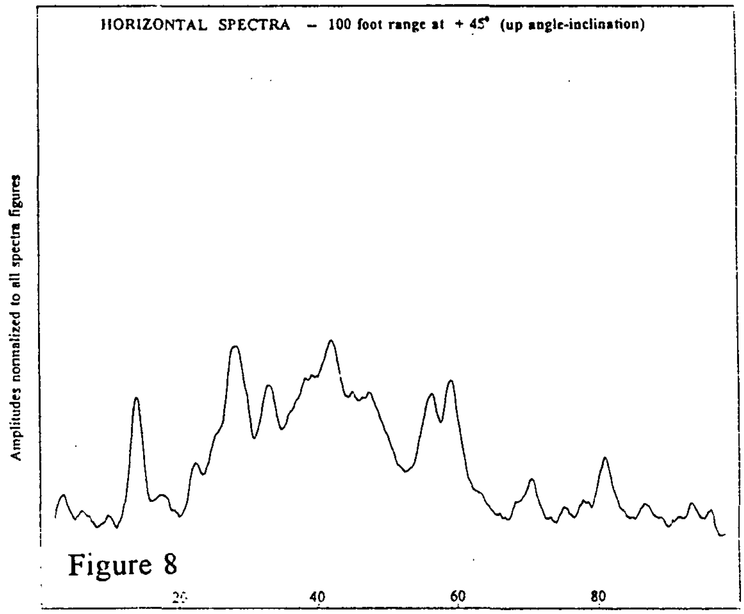

Figure 8

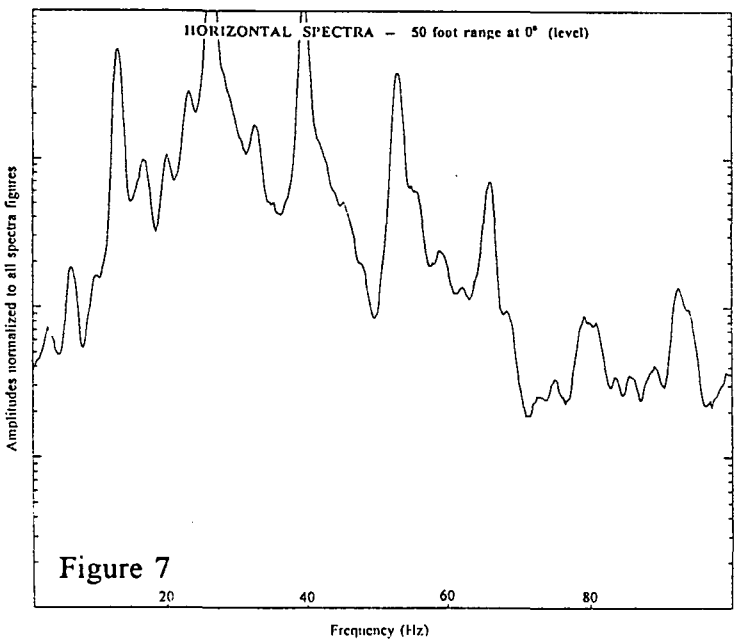

Figure 7

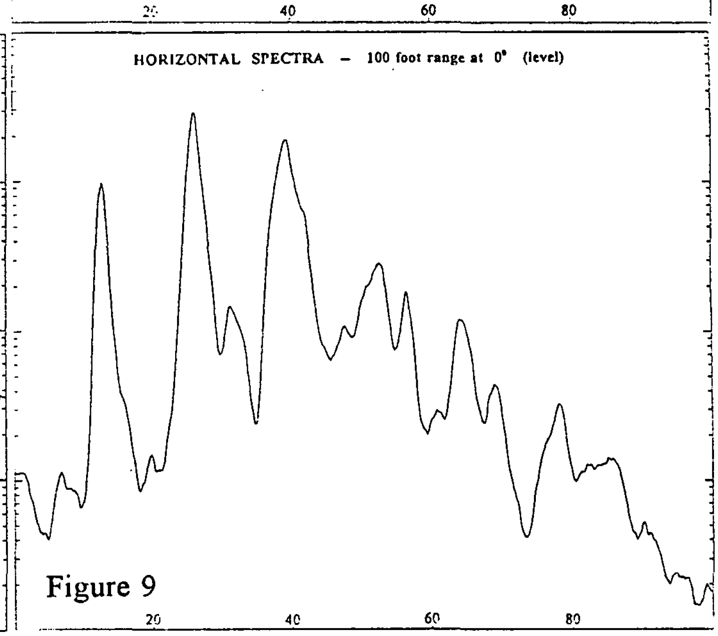

Figure 9

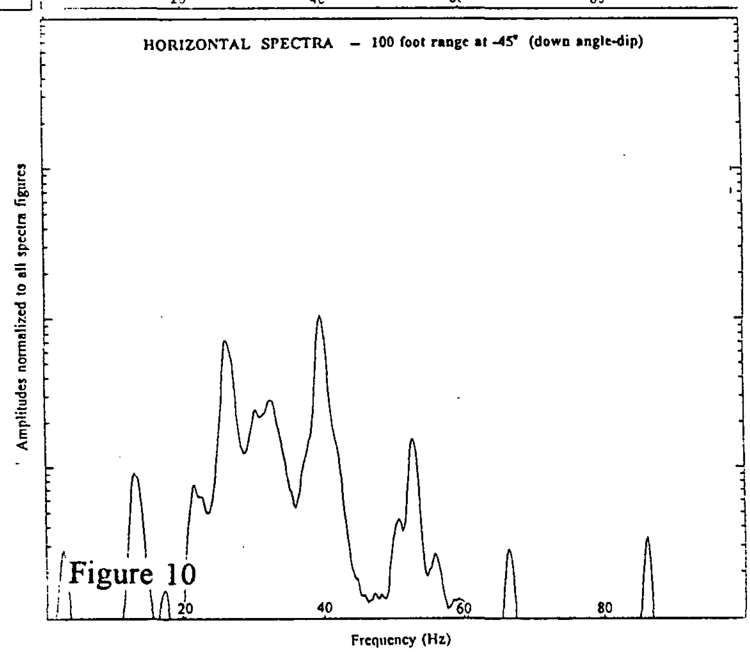

Figure 10

Discussion

The average maximum values from the time-histories and spectra data are shown on Table 1. The induced vibrations from the helicopter at different ranges gave an attenuation function slightly lower than the normal acoustical attenuation in air (inverse of the square of the distance). The variance is probably due to the atmospheric conditions (wind, moisture, etc.), the coupling of the geophone to the rock rather then free-standing in the atmosphere, and the fact that the gepophones were shielded from the direct acoustical waves by a small wall in front of the structures at Balcony House.

The vibration values on the wall were a factor of 3.8 greater then those recorded on the foundation rock . The factor is similar to those found on other archaeological structures. The maximum value observed on the wall for the 50 foot range test was 2.7 mm/sec at 13 Hz. The test was immediately terminated as the value is above the 2.00 threshold value that is recommended. The abrupt termination accounts for the shape of the time-history shown on Figure 4.

The increase in vertical motion in relation to the horizontal vibrations in the +45° plane at the 100 foot range is the result of the more directional, horizontal vibrations dissipating in the atmosphere above the cliff where as the vertical component is more downward focused and is being induced into the rock above and at the structures (Fig 11 detail a).

The larger horizontal vibrations documented from the -45° plane is due to the coupling of the vibration energy directly into the face of the cliff and being efficiently transfered to the dwelling by the rock (c). The vertical vibrations at the -45°, 100 foot range test is approximately the same as those recorded at 0° plane at a 100 foot range.

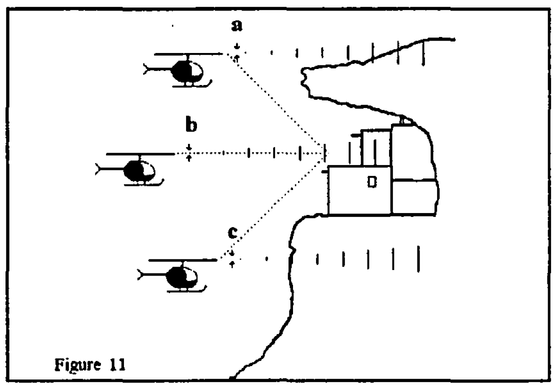

Figure 11

Accurate ranges to the helicopter were not made when the tests were made with an overhead flight (Run #4--Table 1); however, the data and analysis show that the induced horizontal vibrations are increased by a factor of 5 to 6 when the helicopter is level (0°) with the structure. This empirical data confirms the research model by Brentner at NASA in 1991 which suggested that "thickness noise" which is below audible range but in the range of a buildings' natural frequencies, would be radiated from the main rotor in a angular window of plus or minus 10°. This study can not confirm the exact angular window except to say that increase vibrations exist in the 0° plane and does not exist in the 45° or 90° plane (overhead) at the range of 100 feet.

Many engineering reports have stated that the greatest probability of damage to a structure occurs when the structure is excited at its resonance frequency. The frequencies of the vibrations induced by the helicopter are very pure and have one or two peaks in the range of the structures' natural frequencies. The 6 to 26 pure tones or frequencies are the same as the frequency band-widths of many archaeological and historic buildings (King, 1985, 87, 89, 90).

An unknown factor not covered by this report is duration. Several studies have noted that sonic induced vibrations from aircraft or blasts which have a duration 2 to 5 times greater then a blast induced ground vibrations which gave an amplification factor of 1.8 to 2 (Clarkson and Mayes -1992). In general these sonic vibrations are less than 10 seconds. Vibration engineers working with earthquakes have acknowledge that duration of induced vibrations greatly affect the damage risks. (E.V. Leyendecker). It has been noted in many cases that only 2 to 10 more cycles of vibrations would have caused a major catastrophe. Luckily most earthquakes and blasts have very short durations. Helicopter can easily extend the vibration durations by hovering in place.

A second unknown factor is the cumulative effects factor. A Bureau of Mines report states that it would take at least 100,000 repeations to induce an increase effect. A simple calculation would suggest that at approximately 107 minutes cumulative time or approximately 340 passes with a 30sec/ hovering-duration /pass , could increase to the vibration effects.

Summary and Recommendations

-Most helicopters produce vibrations in the frequency band-width of the natural periods of most archaeological or historic structures.
-Relatively light helicopters (2,400 lbs.) hovering within 100 feet and in the 0° plane to a dwelling, produce horizontal induced vibrations at an amplitude that is a high risk to the structures. Heavier helicopters would induce greater amplitudes at low frequencies.
-Duration of hovering time is a factor in the risk of vibration damage.
-The risk is greatly reduced when the helicopters are appreciable above or below the plane of the structure.

Helicopters are a part of the public-environment scene. They are a great help for spot inspections, maintenance, public control, and fire fighting at historic sites. If the audible noise is acceptable, there is no reason that with prudent use that helicopters could not be a help to operations, safety, and public observations of the structures. It would require the complete support and understanding of suitable helicopter use by the pilots.

I would recommend:

1. Short duration (less than 10 seconds) horizontal hovering and flybys can be made within 80 -100 feet of a cliff structure by a light helicopter during critical or inspection situations.
2. No helicopter except those considered critical should hover horizontally to a 1-3 story high historic or archaeological structure within a 150 foot range.
3. Horizontal hovering in the 150 to 200 foot range can be made but should not exceed a 30 sec. duration. Five mile/ hour and faster flybys should not be a vibration risk.
4. Long duration Hovering and flybys in the 300 foot range should present no vibration risk to the structures.
5. Vibration duration and cumulative effects should be of little cause of concern if the 150 and 300 foot criteria are upheld; but, they will greatly increase the risk at or within a 100 foot horizontal range.
6. Helicopters in the 2,400 lb. range can land, take off, and pass over most structures at a 100 foot range without inducing a vibration risk.

This is a set of recommendations for a specific set of structures similar to those investigated. These recommendation are not specific to other structures and should be used only as guidelines. Site specific conditions; bedrock/soils, structure construction, geometry, etc. need to be considered and should include in a site specific tests.

Table 1

Test #1 Helicopter horizontal to recording site				
Component	50' distance amp. mm/sec	100 ' distance amp. mm/sec	200' distance amp. mm/sec	attenuation function
vertical	0.110	0.026	0.007	-1.99
trans. horiz.	0.655	0.197	0.059	-1.74
radial horiz.	0.705	0.209	0.064	-1.73
Test #2 Helicopter at a +45° angle from recording site				
Component		100 ' distance amp. mm/sec	200' distance amp. mm/sec	attenuation function
vertical		0.031	0.006	-2.37
trans. horiz.		0.034	0.009	-1.91
radial horiz.		0.034	0.008	-2.08
Test #3 Helicopter at a -45° angle from the recording site				
Component		100 ' distance amp. mm/sec	200 ' distance amp. mm/sec	attenuation function
vertical		0.016	0.004	-2.02
trans. horiz		0.041	0.011	-1.90
radial horiz.		0.043	0.012	-1.84
Run # 4 Helicopter directly overhead --approximately heights				
Component	50 ' +- above amp. mm/sec	100'+- above amp. mm/sec		
vertical	0.590	0.150		
trans. horiz.	0.182	0.023		
radial horiz.	0.179	0.026		

Author's Note

(Summer-1996)

Through my 40 years of documentation, studying, and leading research teams in the field of induced vibrations to structures, I have noted similarities in the changing of our attitudes toward restricting blasting operations to those of ours today for other sources of vibrations such as aircraft, vehicular, construction and people traffic.

I began studying induced vibrations in the early 1960's and was responsible for predicting the induced vibrations from over 300 individual nuclear tests, approximately 50 very large mine blasts (at approximately 50-100 locations) and the deployment of approximately 20-50 instruments on 10 or more major earthquakes. At the time, we all thought we could set a generic vibration "limit" that would not induce damage to structures and would be accepted by the public. We followed the path of Size of Blast + Distance from house = Amount of house vibrations.

After a few high explosive tests at the Nevada Test Site, using the above formula we were able to set appropriate "limits" for areas such as Las Vegas, Beatty, etc. However, as soon as we moved our tests to other areas like New Mexico, Colorado, or Alaska, we found that our "limits" were not applicable. At the same time, earthquakes were showing damage patterns occurring in places where we would have expected no damage and conversely no damage at many places where we expected damage. Our "limits" at the time were tied by the direct mathematical relationship between the yield of the explosion or the size of the earthquake and distance. A considerable amount of time, talent and money were spend studying the source of the vibrations; the explosion or the fault surface---with very interesting information but -- no <u>improvement</u> in the estimating of damage predictions. Many studies also were made on the attenuation of vibration energy with distance. (I published two studies on attenuation myself). We all wanted a nice clean formula and a set "limit" for damage that would be transferable to all areas.--- It didn't happen. It wasn't until the 1980's that we accepted the premise that damage is "site and building specific".

The mining industry at that time was doing no better. The Bureau of Mines had set a suggested a vibration level for the threshold of damage at approximately 2"/sec based on a study conducted on some homes near a quarry (using size+ distance= damage). The mining operations based their operations on the suggested "limits" and defended them very strongly by quoting the "government study". Structures were being damaged but most mine operators would quote the BoM's publications and would continue operations-as-usual----and ---- the law suits began to grow. As more data became available, the BoM lowered the limit to 1"/sec; then recently to 0.5"/sec. The key problem still existed; communications between the mine owners, government agencies, and the public was generally adversary; and the problem is <u>"site specific".</u>

Approximately 5 years ago a change began to occur with some of the more progressive mining companies. The change was not philanthropy and were certainly instigated by the large settlements made by many companies (one mega settlement was as recently as last month by Amax Co. in Indiana). Some mining companies/public are bringing in outside investigators to document the induced vibrations and develop a set of "limits" that are agreeable to the home owners and to the operations of the mine. (I have help developed a set with BHP mining company at the four corners, the Hunt Midwest Co. in Kansas City, and several smaller operations). Most companies have now recognized that: 1.) the court system will no longer accept the argument that they "were operating according to a set of "standards"; and 2) we have found out that Source + Distance does not give a reliable prediction of the induced vibrations. Today, the key factor for setting protective "limits" for blasts or earthquake codes is "Site Specific". We have accepted that the earth and structures are very heterogenous and that each site carries its own amplification and attenuation factors. The developed formulas for predictions and the "limits" are now used only as guidelines to develop the site specific limits. We also have found out that a limit set by cooperative effort is far better then an adversary court battle or a totally closing of all operations.--note news article. I see a similarity between the setting of limits on aircraft and where we were with blasts in the 1970's. The researchers want to develop a formula which will work in all situations with a great emphasis on the type of aircraft; the operators are tenaciously hanging on to the upper limits that any of these studies produce; and, the public is ready to bane all aircraft. I feel that the only "solution" is a cooperative effort which will not shut down all operations but will find an acceptable area or zone that operations can continue.

The more recent BoM publication lowered the level to 0.5 "/sec (12.5 mm/sec) and have stated that some damage at selected structures can occur below that level. The vibration limit for one-of-a-kind, irreplaceable structures should be approximately 2mm/sec as shown in several past reports: Chaco Canyon, Mesa Verde, etc. One point to note: low vibrations can induce microcracks in adobe-stone type structures. These cracks though not "damage" will allow moisture to invade the structure and will result in "water" damage.----what caused the damage ?? microcracks or the water??? Keep the vibration levels at irreplaceable, masonry, structures below 2 mm/sec.

Romer backs helicopter ban

Rocky Mountain National Park---- Gov. Roy Romer has told federal officials he supports a ban on helicopter tours over Rocky Mountain National Park.

"Citizens in this area have made it clear that helicopter tours of the park would be inconsistent with the long-term economic development goals and quality of life in their communities," Romer said in a letter Friday to the Federal Aviation Admin- istration. Transportation Secretary Federico Pina visited Rocky Mountain National Park in May and voiced his support for an FAA proposal to ban heli- copter tours.
(July 28, 1996-Denver Post)

Report

The enclosed report has not as yet been published. It is provided for your discretionary review and enable you to understand the capabilities of geotech site testing. I was able to gather the data as a side effort to another program due to a unique set of circumstances. An informal agreement which would have allowed me the money and time to analyze the data and publish a report was not finalized due to NPS personnel and budget changes. I was able to get the data due to the support and foresight of Robert Hyder (then superintendent at Mesa Verde) and Jack Smith (Archaeologist) who both have since retired- (so have I, but I am now consulting). With the advent of the home PC computers and a little free time in my retirement-consulting, I am now able to produce a synopsis of the data and analysis. I believe it should be known to personnel who have the responsibility of protecting or preserving the archaeological and historic sites. The report will avoid the verbiage boilerplate which is needed for a formal report. The equipment descriptions, calibrations, references, etc. can be found in my reports on Chaco Canyon, White Sands, Mesa Verde, etc. I have a considerable collection of vibration examples from many sources. Within that collection, I have data from helicopters at White Sands, Hovenweep, Phoenix, Laguna, and Taos. I did not include the full suite of data in this report as it is beyond the time I now have available----maybe next year. If you have any questions, give me a call. Please xerox the report and pass it around. I made a limited mailing as the costs gets a little prohibitive for a mass mailing.

Commercial

I decided to use the report rather then a newsletter this year. This year I have worked on air traffic vibrations at a Florida location, blasting and vehicle vibration problems at Gracemor, Mo., a USFS archaeological structure in New Mexico, a vibration problem at Pipe Springs, and a continuing study of traffic and road building vibration effects at an archaeological site in Ark. and Mo. I still believe that site managers need vibration "zone" information of their area which would show where certain types of equipments could operate safely and where they would be a risk to the structures. The study is technically defensible and site specific. A strong tool for many decisions made during these times of expanding public and political pressures.

Remember me for the year-end moneys and for next years budget. My costs are still the same. Below $2,000-$5,000 for most investigations. Conversations are free. Give me a call .