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QUANTIFICATION OF HELICOPTER VIBRATION RIDE QUALITIES

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ABSTRACT

This paper presents a discussion of absorbed power as a means for quantifying helicopter vibration ride quality. Absorbed power is a measure of the rate at which the body absorbs energy when subjected to vibration. It has been used effectively as a quantitative measure of ride quality for ground vehicles, but it has not been used to quantify aircraft ride quality; thus, this paper presents an initial evaluation of helicopter vibration ride quality using absorbed power. Vibration data were measured on five different operational US Army helicopters and were converted to absorbed power using human body transfer functions measured by researchers of the US Army Tank Automotive Command, the originators of the absorbed power concept. In addition, subjective data regarding helicopter ride quality obtained by earlier investigators were converted to absorbed power. The earlier data indicated that constant absorbed power might be a meaningful way to specify helicopter ride quality requirements over a broad frequency range of interest in helicopter dynamics. The absorbed power measurements obtained from the operational helicopters fell between the levels for acceptable ride quality of automobiles and off-road vehicles. Further tests are planned to obtain subjective responses to the helicopter vibrations and to correlate these responses with the absorbed power measurements.

1. INTRODUCTION

The specification of acceptable helicopter vibration levels in terms of acceleration has been common practice for many years, and acceleration is a proper measurement parameter for pure vibration. Acceleration is also a proper specification parameter in defining an acceptable vibration environment for mechanical and electronic equipment. However, if the purpose of specifying vibration levels is to guarantee a vibration environment in which the pilot and crew can function efficiently, or in which passengers are comfortable, then acceleration may not be the best measure of the vibration environment. Subjective evaluation of vehicle ride qualities accounts for such factors as human body vibration, physical environment, exposure duration, and noise in addition to the vehicle acceleration levels. Subjective evaluations of vehicle ride qualities tend to be somewhat subject-dependent, and therefore a statistical approach must be used in order to obtain reliable information. This necessitates numerous tests with numerous subjects, which equates to high cost.

Whole-body vibration of humans is a subject around which an entire field of scientific literature has developed. Kidd, in an excellent recent paper assessing the problems associated with development of realistic helicopter vibration criteria related to ride comfort (Ref. 1), points out that this body of literature has grown rapidly since the early 1930's. Kidd also discusses some of the approaches which have been taken to quantify vehicle vibration ride quality and the difficulties in relating subjective responses to measured vibration quantities such as acceleration level, vibration frequency, and exposure duration.

In an effort to determine a measurable parameter which correlates well with subjective evaluations of vehicle ride quality, the US Army Tank Automotive Command (TACOM) has conducted an extensive amount of research on whole body vibration. They have concluded that if one measures the rate at which the body absorbs energy during vibration tests, this parameter and subjective responses may be correlated (Ref. 2). The parameter, referred to as Absorbed Power, has been used by TACOM to evaluate the ride quality of ground vehicles such as tanks, trucks, and automobiles. In general, they have found that constant subjective response correlates well with constant absorbed power.

The purpose of this paper is to present, for the first time, an evaluation of the vibration environment on several operational US Army helicopters using the absorbed power parameter. The absorbed power parameter is discussed, its application to some previous subjective response data and ISO 2631 Standard (Ref. 3) curves are shown, and quantification of the vibration environment on some Army helicopters are presented using absorbed power.

2. ABSORBED POWER

As a result of vibration tests in a ride simulator, TACOM researchers made two observations (Ref. 4): First, the more relative motion occurring between various parts of the body, the more severe the vibration; and second, doubling the amplitude of the vibration more than doubled the severity. These observations led to postulation of the theory, "The severity of a vibration is proportional to the rate at which the body is absorbing energy." Mathematically, this may be expressed as

$$P_{avg} = \lim_{T \to \infty} \frac{1}{T} \int_0^T F(t)\, V(t)\, dt \tag{1}$$

where P_{avg} = average power absorbed by the subject

$F(t)$ = input force on the subject

$V(t)$ = velocity of the subject

T = averaging time interval

If the input force is written as

$$F(t) = \sum_{i=0}^{n} F_i \sin (w_i t + \emptyset_i) \tag{2}$$

and the velocity as

$$V(t) = \sum_{i=0}^{n} V_i \sin w_i t \qquad (3)$$

then the average power absorbed becomes (Ref. 4)

$$P_{avg} = \sum_{i=0}^{n} \frac{G(jw_i) \sin \phi_i}{w_i} A_i^2 = \sum_{i=0}^{n} K_i A_i^2 \qquad (4)$$

where A_i = rms acceleration of the subject at frequency w_i

w_i = frequency of vibration

ϕ_i = phase angle between force and velocity

$G(jw_i)$ = Transfer function that relates force to acceleration $G(jw) = F(jw)/A(jw)$

j = imaginary number, $j = \sqrt{-1}$

Note that the units of absorbed power are watts.

It may be noted that the transfer function G(jw) represents the equivalent mass of the subject being vibrated. This transfer function was obtained experimentally by TACOM for seated subjects by measuring the vibration responses of 21 volunteer subjects in over 1400 hours of testing. The tests resulted in the transfer functions for vertical, fore-aft, and side-to-side vibrations as well as for vibrations applied at the feet of the subjects. The experimental results for all the test subjects were averaged to obtain the mathematical transfer functions describing the vibration response characteristics of an average young male (28 years) of approximately 150 pounds seated weight. More detailed information on the test subject characteristics may be found in Ref. 5. The average transfer functions for vertical, fore-aft, and side-to-side accelerations are reproduced from Ref. 5 for information and shown in Figs. 1 through 3. With the transfer functions thus obtained, the power absorbed by subjects who fall in the category of the test subjects may be easily obtained once the vibration environment is known. Some examples of absorbed power calculations may be found in Ref. 6.

Some important observations regarding absorbed power have become clear from the TACOM research. First, absorbed power has a physical significance and therefore can be measured or computed analytically. Secondly, absorbed power is a scalar quantity; hence, for multidegree of freedom systems, individual absorbed power values may be summed to obtain a single quantitative measure of human vibration. Finally, absorbed power can be used for periodic, aperiodic, and random vibrations.

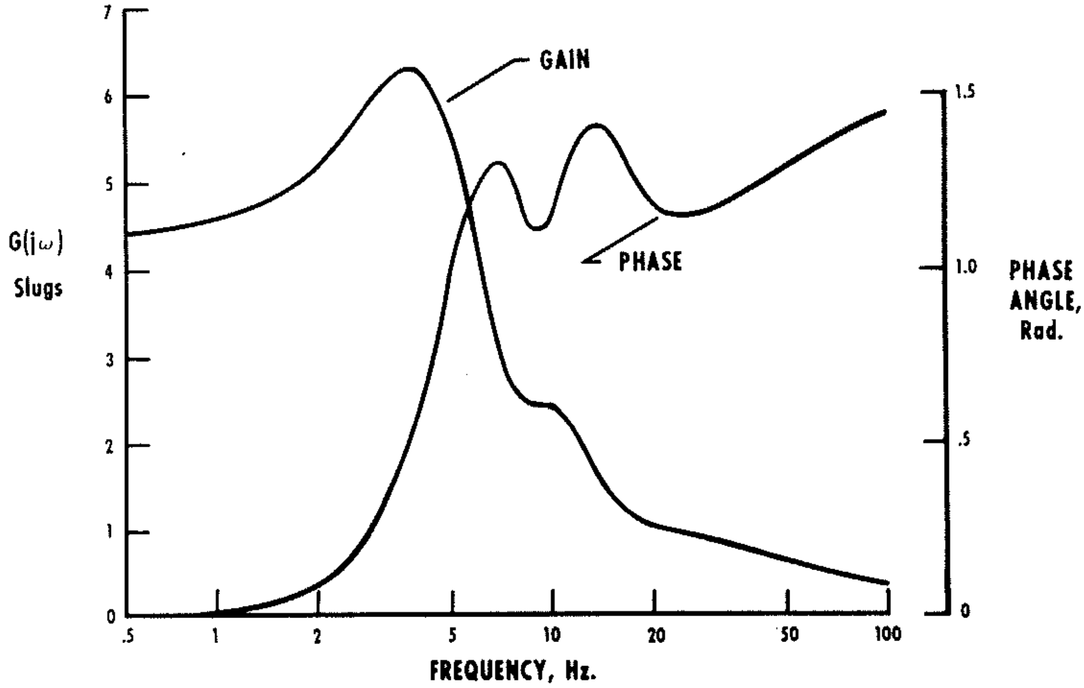


Figure 1. Vertical equivalent mass for seated subject.

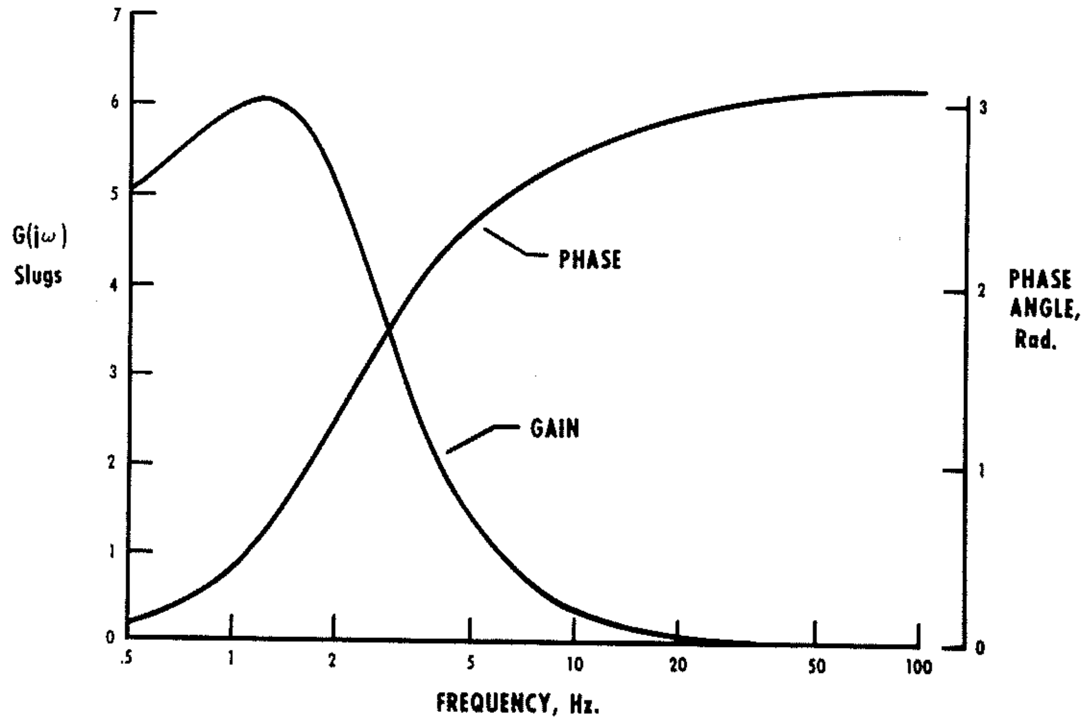


Figure 2. Fore-aft equivalent mass for seated subject.

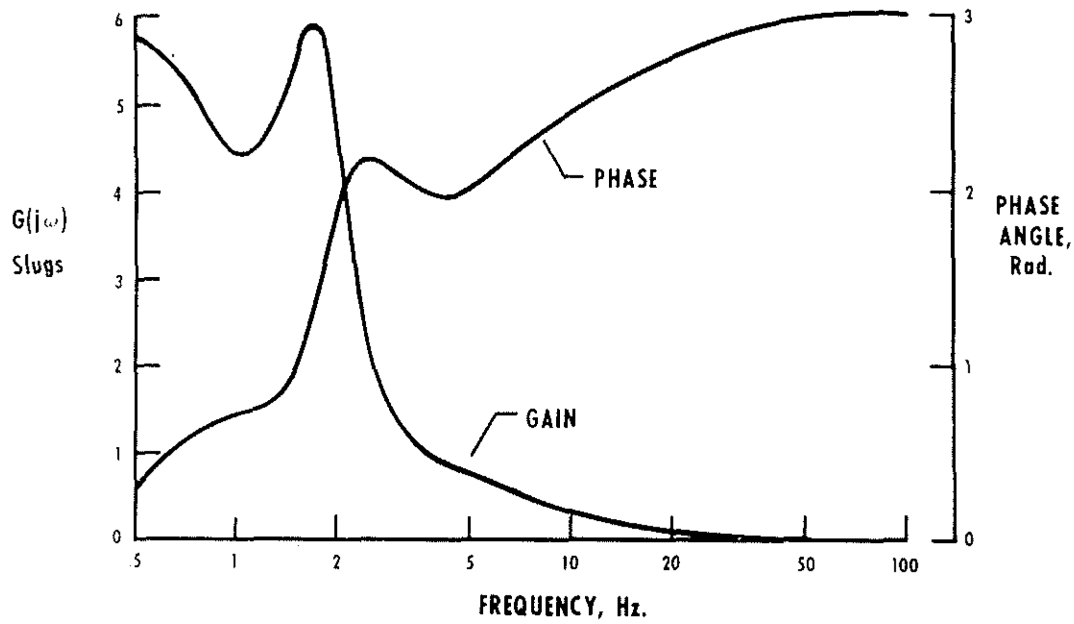


Figure 3. Side-to-side equivalent mass for seated subject.

It is important to note that physical environment also plays a role in determining the acceptable level of vibration ride quality. In terms of absorbed power, the TACOM testing has shown that about 6 watts is the limit of acceptability for cross-country vehicles, whereas the limit for automobiles is .2-.3 watt. Absorbed power has not been previously used for aircraft, so a direct comparison with subjective responses is not currently possible. In subsquent sections, quantification of vibration on various helicopters in terms of absorbed power will be presented. It is planned that at a later date the helicopter vibration accelerations will be used in conjunction with the NASA-Langley Research Center Passenger Ride Quality Apparatus (Ref. 7) to obtain subjective assessments of helicopter ride quality.

3. APPLICATIONS OF ABSORBED POWER

Gabel et al, (Ref. 8), describe some research conducted by Boeing Vertol in evaluating human reaction to the helicopter vibration environment. The tests, using helicopter pilots as subjects, were conducted by vibrating a helicopter seat in which the subjects were seated and obtaining subjective reaction to the vibration. In Ref. 8 the authors reviewed the work by TACOM researchers in developing the absorbed power measurement and recommended its application in assessing helicopter ride quality, but they presented no application to their data.

In Fig. 4 a curve representing "acceptable comfort for 2-3 hour exposure" from the Vertol tests is reproduced from Fig. 2 of Ref. 8. The curve is shown in terms of vertical acceleration as presented in Ref. 8, and the data are also converted to absorbed power using the vertical transfer function of Ref. 5. As may be seen from Fig. 4, beyond approximately 12 Hz the acceptable comfort curve corresponds to roughly constant absorbed power. The peak in the absorbed power curve at approximately 4.5 Hz is due to a human body natural frequency which occurs between 4 Hz and 7 Hz for various individuals. This vibration mode is thought to be caused by the mass above the diaphragm resonating, with the diaphragm acting as a spring (Ref. 4). The increased relative motion of the organs within the body at resonance results in an increase in the amount of energy absorbed by the body.

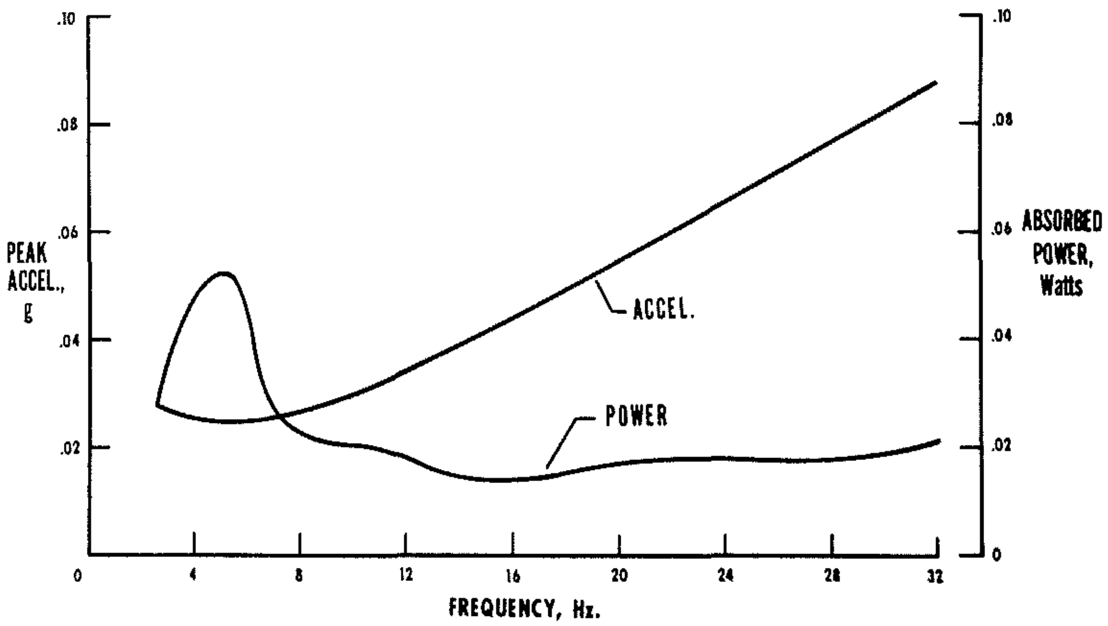


Figure 4. Conversion of Boeing Vertol subjective evaluation to absorbed power.

In a second application of the absorbed power parameter, one of the curves from ISO 2631 (Ref. 3) is presented in Fig. 5 in terms of acceleration and absorbed power. The curve represents the 8-hour "Fatigue - decreased proficiency boundary" for vibration in the vertical direction (along spinal direction in seated position). In this case it may be seen that the absorbed power for the "decreased proficiency boundary" is increasing only slightly beyond approximately 15 Hz. Below this frequency, two peaks in the absorbed power curve are evident. The large peak at approximately 5 Hz corresponds to the body natural frequency discussed earlier; and the peak at roughly 12.5 Hz represents a second body natural frequency that is believed to be caused by a resonating condition in the spinal column (Ref. 4).

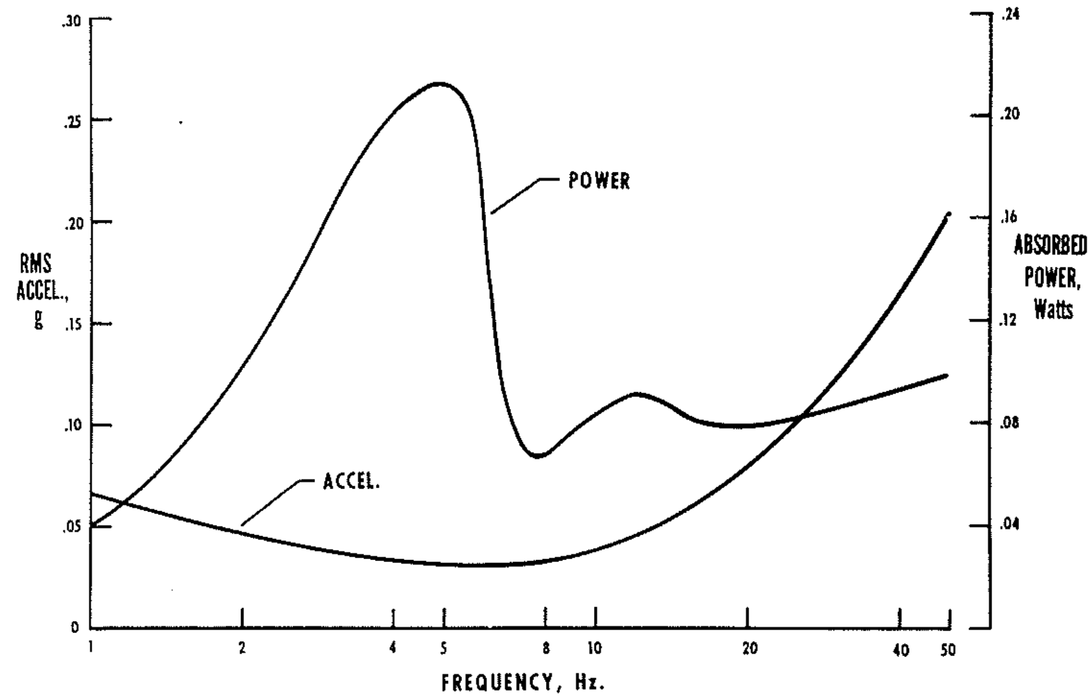


Figure 5. Conversion of ISO 2631 8-hour fatigue-decreased proficiency boundary to absorbed power.

From Figs. 4 and 5 two observations may be noted. First, the frequency range in which the body tends to absorb the most energy (4-7 Hz) is the range in which the rotational speed of most currently operational helicopters will occur. The fact that the body absorbs more energy in this range might be the reason why any rotor unbalance or out-of-track condition is so readily obvious and objectionable to pilots and passengers. Secondly, in the frequency range of particular interest from a rotor-transmitted vibration point of view (approximately 12-40 Hz) there is only a slight increase in the absorbed power, indicating that a constant absorbed power criterion might be a meaningful way to specify vibration ride quality.

As a result of the above observations it was decided to obtain vibration measurements on a number of operational US Army helicopters and to evaluate the vibration environments on the various helicopters in terms of absorbed power. The following sections describe the tests and the results of the measurements.

4. TEST HELICOPTERS AND MEASUREMENT TECHNIQUES

The test aircraft chosen were representatives of each helicopter type presently operational in the active US Army. Included were a Bell UH-1H Iroquois, a Bell OH-58C Kiowa, a Bell AH-1S modernized TOW Cobra, a Boeing Vertol CH-47C Chinook, and a Sikorsky UH-60A Blackhawk. Aircraft and flight crews for the test flights were provided by the Aviation Maintenance

Management Training Division of the US Army Transportation School at Fort Eustis, Virginia. The various aircraft used in the tests are shown in Fig. 6. The aircraft were operational fleet aircraft, and no attempt was made to adjust or refine the tuning of any vibration control devices which may have been on the respective aircraft as standard equipment. The purpose of the tests was not to conduct an extensive vibration survey of each aircraft, but rather to obtain representative data to use in evaluation of absorbed power as a measure of helicopter ride quality.

Two sets of instrumentation were carried on board each test flight. The first set was for vibration measurements; it consisted of a triaxial accelerometer package connected to a seven-channel analog tape recorder. The second set was for recording aircraft internal noise data; it consisted of a Nagra acoustical tape recorder and two acoustical microphones. The noise data collected will be used in conjunction with vibration data in an ongoing joint NASA-Army ride quality program of which this current research is a part. All instrumentation was provided by the Noise Effects Branch of NASA-Langley Research Center.

The accelerometer package was placed as close as possible to the base of the pilot's seat and the acoustical microphones were located near the pilot's and copilot's heads. Vibration and sound recordings were then taken for a period of approximately 30 seconds at each of the following conditions: hover in-ground effect (IGE), hover out-of-ground effect (OGE), rearward flight, left and right sideward flight, 500 fpm climb at cruise velocity, and forward level flight speeds from 10 knots to maximum level flight speed for the respective aircraft.

It was originally intended that the absorbed power measurements would be made directly from the recorded vibrations using an instrument developed by TACOM for that purpose (Ref. 4). However, during the data reduction process it was determined that the instrument electronics were optimized for the vibration levels and frequencies characteristic of ground vehicles; as a result, the instrument did not provide accurate absorbed power data for the helicopter vibrations. Consequently, the absorbed power measurements were obtained from the recorded vibrations using a computer program implementation of the absorbed power equations.

5. DISCUSSION OF RESULTS

The absorbed power results obtained from the vibration measurements on the respective aircraft are shown in Figs. 7 through 9 as a function of forward flight speed. The zero airspeed results shown are for hover OGE. For the test conditions other than forward flight mentioned earlier, the absorbed power values were in the same range as the forward flight values.

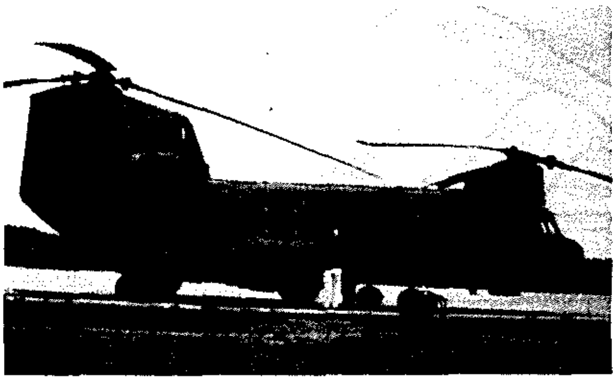
As was expected, the absorbed power results vary considerably between aircraft. The trends of absorbed power with forward speed for vertical vibrations show the same behavior as the more familiar vibration trends, increasing with speed beyond about 60 knots. For vertical vibration the absorbed power results indicate that the helicopter ride quality is better than the acceptable level for off-road ground vehicles and slightly worse than the acceptable level for automobiles. This observation seems to agree with one's intuition regarding where the helicopter ride should fall in comparison with these other vehicles.

(a) UH-1H

(b) AH-1S

(c) OH-58C

(d) UH-60A



(e) CH-47C

Figure 6. Helicopters used to obtain vibration data for absorbed power evaluation.

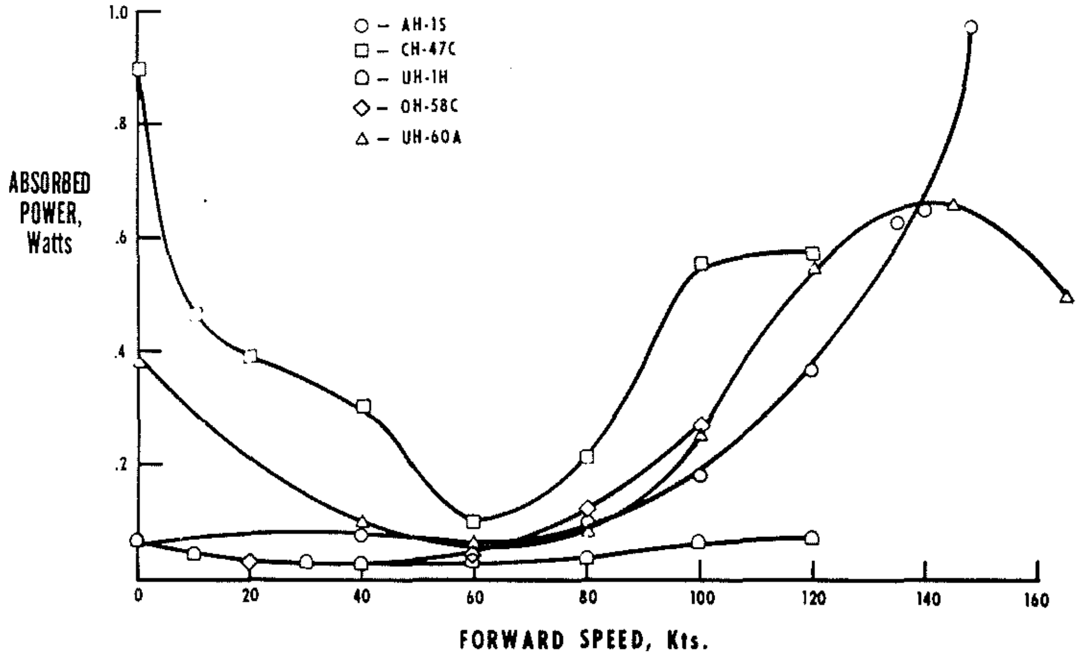


Figure 7. Absorbed power from vertical acceleration for helicopters tested.

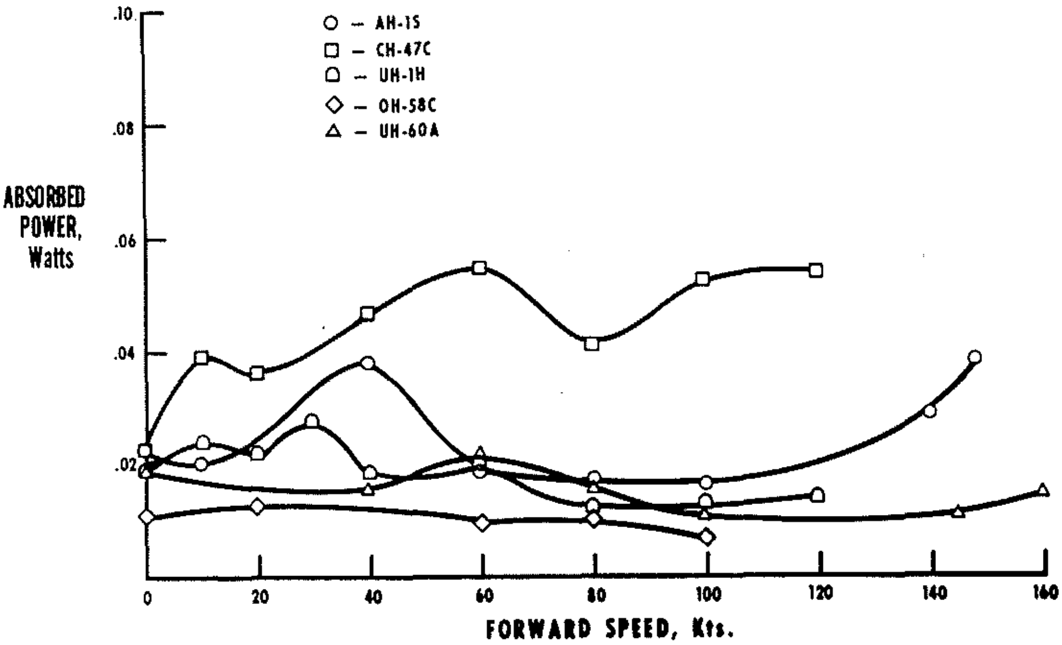


Figure 8. Absorbed power from fore-aft acceleration for helicopters tested.

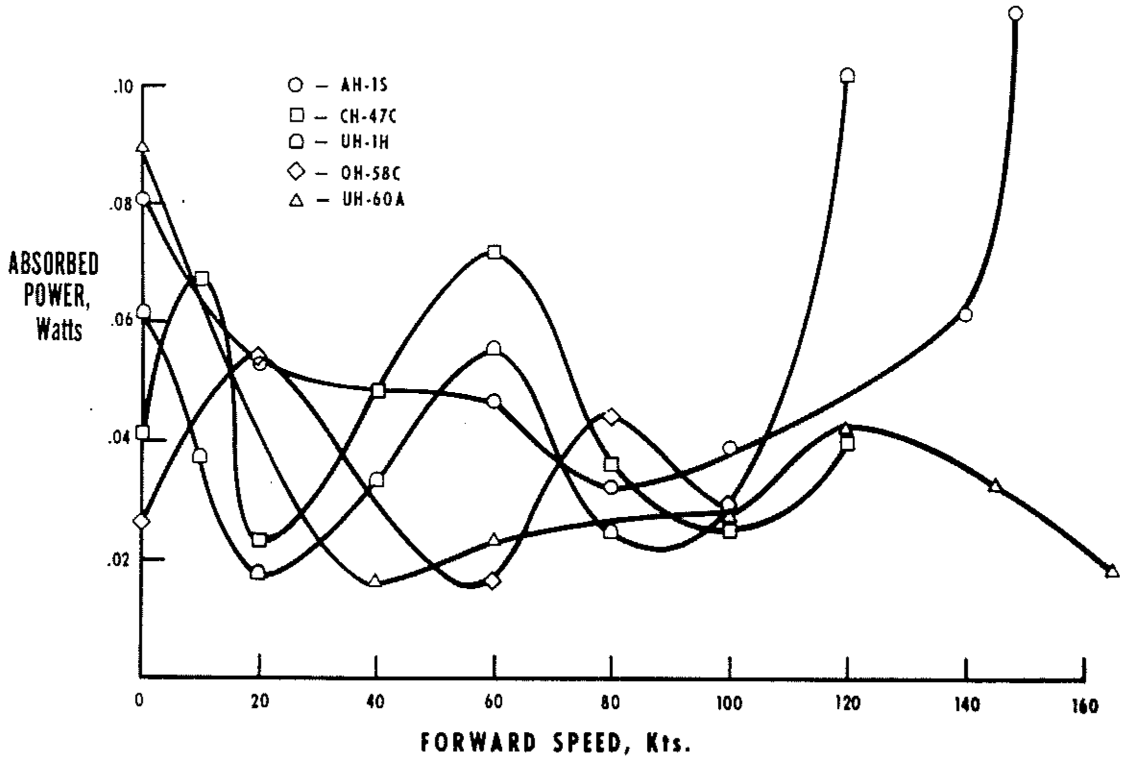


Figure 9. Absorbed power from side-to-side acceleration for helicpters tested.

As may be seen from Figs. 8 and 9, the fore-aft and side-to-side absorbed power values are roughly an order of magnitude less than the corresponding vertical values. This result stems from lower vibration levels in the fore-aft and side-to-side directions as well as the fact that the body transfer functions for these directions would indicate that the body absorbs less energy in these directions at the frequencies of importance in helicopter vibrations than in the vertical direction. The significant frequencies for the aircraft tested are shown in Table 1.

Table 1. Significant frequencies for vibration considerations on helicopters tested

			FREQUENCY, HZ.			
AIRCRAFT	1P	2P	3P	4P	6P	8P
CH-47C	3.9	-	11.8	-	23.5	-
UH-60A	4.4	-	-	17.5	-	35.1
UH-1H	5.4	10.8	-	21.6	-	43.2
AH-1S	5.4	10.8	-	21.6	-	43.2
OH-58C	5.9	11.8	-	23.6	-	47.2

With respect to Table 1, an observation regarding the application of absorbed power for evaluation of helicopter vibration ride quality may be made. It is well known that the significant vibrations in the helicopter airframe occur at frequencies corresponding to integer multiples of the main rotor rotational speed. Further, the vibrations of most concern occur at the rotor rotational frequency (one-per-rev) and N times the rotational fre-quency (N-per-rev, or blade passage frequency) where N is the number of blades. Thus, when assessing the vibration levels in a particular helicopter, the evaluation is generally made on the basis of the highest level at these discrete frequencies. Absorbed power, on the other hand, is based on the complete frequency spectrum of the vibration. By observing the spectrum of the absorbed power one can see that the largest contributions to absorbed power for the helicopter vibrations occur at the integer multiples of the rotor speed, but the value of absorbed power at a particular flight condition accounts for all these frequencies. It is felt that the advantage of using absorbed power as a measure of helicopter ride quality is that it does account for vibration at all frequencies in the spectrum, properly weighted to reflect the response of the body at various frequencies.

It is of interest to compare the results of Fig. 7 with Gabel's (Ref. 8) curve, Fig. 4, respresenting "acceptable comfort for 2-3 hour exposure," and the ISO 2631 curve, Fig. 5, representing "8-hour fatigue-decreased proficiency boundary." For the most part, the absorbed power results of Fig. 7 are greater than the absorbed power for either of these "boundaries." Using the dominant frequencies of vibration for the aircraft tested, Fig. 4 would indicate that the absorbed power level should be below .02 watt and Fig. 5 would indicate that the level should be less than .09 watt. At 60 knots all the aircraft would satisfy a .09-watt requirement, but at speeds above 80 knots only one aircraft would satisfy this criterion. Below 60 knots three of the aircraft would satisfy a .09-watt requirement. None of the helicopters tested could meet an absorbed power level requirement given by Fig. 4.

6. CONCLUDING REMARKS

A preliminary evaluation of absorbed power as a means for quantifying helicopter vibration ride quality has been made. Absorbed power seems to offer certain advantages over raw acceleration measurements and subjective responses for evaluation of ride quality. The most important attribute of absorbed power is that it represents a measurable quantity of physical significance which accounts for both the vibration levels and the human body response to the vibration. Past research has shown that absorbed power correlates well with subjective responses for ground vehicles.

Absorbed power measurements obtained on five operational US Army helicopters have been presented here. In addition, vibration data previously obtained by other researchers indicating acceptable subjective response for helicopter vibration levels and ISO 2631 reduced proficiency boundaries were converted to absorbed power for comparative purposes. It was found that the absorbed power measurements from the operational helicopters were, in general, higher than the values from these comparative boundaries.

Current plans are to continue evaluation of the absorbed power parameter as a means of quantifying helicopter vibration ride quality. In a joint program with NASA-Langley Research Center, the measured vibrations from the operational Army helicopters will be used in an airline-configured ride simulator to obtain subjective responses using helicopter crew subjects. These subjective responses will permit calibration of absorbed power for helicopter vibration environments. In addition, the subjective responses will be used to evaluate a NASA-developed ride quality prediction model which makes use of both vibration and noise measurements in assessing vehicle ride quality.

7. REFERENCES

1 D. L. Kidd — Assessment of Helicopter Vibration Criteria. American Helicopter Society Preprint No. 81-22, 37th Annual Forum of the American Helicopter Society, New Orleans, LA, May 1981.

2 F. Pradko, R. A. Lee, and J. D. Greene — Human Vibration Response Theory. American Society of Mechanical Engineers, Paper 75-WA/HUF-19, Winter Annual Meeting, Chicago, IL, November 7-11, 1965.

3 Anon. — Guide for the Evaluation of Human Exposure to Whole Body Vibration. International Standard ISO 2631, 1978.

4 R. A. Lee and J. Cumbow — Absorbed Power Ride Measurement Instrument. US Army Tank-Automotive Research and Development Command Technical Report 12415, December 1978.

5 W. F. Lins — Human Vibration Response Measurement. US Army Tank Automotive Command Technical Report No. 11551, June 1972.

6 R. A. Lee and F. Pradko — Analytical Analysis of Human Vibration. Society of Automotive Engineers, Paper 680091, Automotive Engineering Congress, Detroit, MI, January 8-12, 1968.

7 S. A. Clevenson, and J. D. Leatherwood — On the Development of Passenger Ride Acceptance Criteria. Shock and Vibration Bulletin, Bulletin 43, Pt. 3, US Department of Defense, June 1973.

8 R. Gabel, B. O. Henderson, and D. A. Reed — Pilot and Passenger Vibration Environment Sensitivity. Journal of the American Helicopter Society, Volume 16, No. 3, July 1971.