Bulletin 53
(Part 1 of 4 Parts)

THE SHOCK AND VIBRATION BULLETIN

Part 1

Welcome, Keynote Address,
Invited Papers, Pyrotechnic Shock, and
Shock Testing and Analysis

MAY 1983

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The 53rd Symposium on Shock and Vibration was held at the Radisson Ferncroft Hotel, Danvers, MA on October 26-28, 1982. The U.S. Army Materials and Mechanics Research Center, Watertown, MA, was the host.

Office of
The Under Secretary of Defense
for Research and Engineering

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SESSION CHAIRMEN AND COCHAIRMEN

Date	Session Title	Chairmen	Cochairmen
Tuesday, 26 Oct. A.M.	Opening Session	Mr. Richard Shea, U.S. Army Materials and Mechanics Research Center, Watertown, MA	Mr. Henry C. Pusey, Shock and Vibration Information Center, Naval Research Laboratory, Washington, DC
Tuesday, 26 Oct. P.M.	Elias Klein Memorial Lecture Plenary A	Mr. Henry C. Pusey, Shock and Vibration Information Center, Naval Research Laboratory, Washington, DC	
Tuesday, 26 Oct. P.M.	Machinery Dynamics	Dr. Ronald L. Eshleman, The Vibration Institute, Clarendon Hills, IL	Mr. Samuel Feldman, NKF Engineering Associates, Inc., Vienna, VA
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Tuesday, 26 Oct. P.M.	MIL-STD-810D Panel Session	Mr. Preston Scott Hall, Air Force Wright Aeronautical Laboratories, Wright Patterson Air Force Base, OH	Mr. Rudolph H. Volin, Shock and Vibration Information Center, Naval Research Laboratory, Washington, DC
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Wednesday, 27 Oct. A.M.	Vibration: Test and Criteria	Mr. John Wafford, Aeronautical Systems Division, Wright Patterson Air Force Base, OH	Mr. Howard D. Camp, Jr., U.S. Army Electronic Research and Development Command, Ft. Monmouth, NJ
Wednesday, 27 Oct. A.M.	Shock Testing and Analysis	Mr. Edwin Rzepka, Naval Surface Weapons Center, Silver Spring, MD	Mr. Ami Frydman, Harry Diamond Laboratories, Adelphi, MD
Wednesday, 27 Oct. P.M.	Damping	Dr. Frederick C. Nelson, Tufts University, Medford, MA	Dr. Lynn Rogers, Air Force Wright Aeronautical Laboratories, Wright Patterson Air Force Base, OH
Wednesday, 27 Oct. P.M.	Fluid-Structure Dynamics	Dr. Anthony J. Kalinowski, Naval Underwater Systems Center, New London, CT	Dr. Martin W. Wambsganss, Argonne National Laboratory, Argonne, IL
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Thursday, 28 Oct. A.M.	Vehicle Dynamics	Dr. Richard A. Lee, U.S. Army Tank-Automotive Command, Warren, MI	Dr. Grant R. Gerhart, U.S. Army Tank-Automotive Command, Warren, MI
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WELCOME

Dr. Edward S. Wright
Director
U.S. Army Materials and Mechanics Research Center
Watertown, MA

I would like to officially welcome all of you to the 53rd Shock and Vibration Symposium. Just the fact that there have been 53 of them speaks very well for the history and stature of the symposium. It obviously has been held at the highest level of standards in the past, and a review of the program for this one indicates that it is certainly no exception. It appears to be outstanding. The symposium offers a key mechanism for the interchange of information in the shock and vibration field between government, industry and universities, and we feel it is extremely valuable.

Since many of you will be visiting the Army Materials and Mechanics Research Center later in the week, either to attend the classified sessions that will be held there, or to tour our laboratories, I would like to tell you a little bit about our Center while you are here. It also gives me the opportunity to do a little propagandizing or P.R. work. As I have been asked several times, "What's an AMMRC?"; I will tell you a little bit about that.

Basically, we are a corporate lab of DARCOM, the Army Materiel Development and Readiness Command; this is the part of the Army that is responsible for developing, procuring, and supplying to the field, all of the military equipment for the Army. We are responsible for research and development in the areas of materials and mechanics for the total DARCOM community.

We are located about six miles due west of Boston. We are in the center of a number of very well-known universities; we are also located near some other government agencies, such as the Air Force Electronics Systems Division at Hanscom Field, and the Department of Transportation's Research Center. We are on the site of the old historic Watertown Arsenal. The Arsenal, as such, was one of the many arsenals closed during the 1960's, and a portion of what was the Arsenal evolved into the Army Materials and Mechanics Research Center.

We are one of the three labs, out of about 20 DARCOM labs, that report directly to the Headquarters. So basically, we are a corporate lab, and as such, we work for all of the systems development commands. We do not have a specific system development responsibility ourselves, but we are responsible for supporting all of the other commands. That means I have many bosses, one of whom is sitting on my right and will be giving your Keynote Address: General Stevens, who commands AVRADCOM, the Army Aviation Research and Development Command.

We work not only for the development commands, but also for the readiness commands, which actually procure and supply the equipment to the field forces. We also work for the project managers who are responsible for the development and the production of major systems such as the Abrams tank, the Bradley Fighting Vehicle and the Apache attack helicopter. We have a research and development mission of our own, but one of our greatest reasons for being is the support that we give, not only to these Army organizations, but to their contractors as well. Quite often it is the contractors that first see the materials problems either in development or production.

I mentioned that we have a research and development mission. Basically, we are the lead lab, as designated by DARCOM, in the areas of materials, solid mechanics, and materials testing technology. In this context, testing technology refers to testing for the purposes of accepting materials and components for use in systems, rather than testing associated with our research and development mission.

Current emphasis includes materials processing, and the characterization of materials to ensure reliability and reduce costs in future systems. I will not discuss our various areas of interest at this time, since you will see examples of this work when you visit us.

In addition to our basic R&D mission we perform many other functions, and foremost among them is the support we provide to the systems developers. I would like to point out one other item; that is the management of information and analysis centers. These are portions of the DOD Information and Analysis Center Program that are paid for out of DLA funds but administered by the three services. We are responsible for three information analysis centers: Metals and Ceramics Information Center which is located at Battelle, Thermo-Physical and Electronic Property Center, and the Non-Destructive Testing Information and Analysis Center (NTIAC). NTIAC is somewhat similar to the Shock and Vibration Information Center (SVIC). We ran NTIAC in-house at the Army Materials and Mechanics Research Center for a long time, just as the Naval Research Laboratory still runs SVIC. I can well appreciate some of the trials and tribulations that Mr. Psey and his staff must endure, based upon our own similar experience. I do feel that SVIC is doing an out-standing job. We help support the SVIC, and we certainly benefit from what it does. We hope to continue our close relationship with the Center.

I feel shock and vibration is very important to AMMRC. Many aspects of the work that we do for the Army involves shock and vibration. We are responsible for research on armor and penetrator materials and for the development and evaluation of armor materials and penetrator materials for Army systems. In the mechanics area we are concerned with the interaction of armor and penetrators, and I think that this is the epitome of the shock regime. We also get involved in vibration problems. For example, we do quite a lot of work on that "flying fatigue machine" known as the helicopter. So we are deeply interested in the shock and vibration business, and appreciative of the efforts of SVIC.

I would like to preview some of the facilities and activities that you will see during your visit to AMMRC. For example, we have set up a new range within the last few years to work on quarter-scale modeling of both long rod, high density penetrators, and armors designed to defeat such penetrators. The full scale penetrators are fired out of 120 millimeter or 155 millimeter tank cannons. We can launch quarter-scale projectiles up to about 6,000 ft/sec in the firing range, and study the penetrator-armor interaction process. Going to higher shock regimes, you will also see our slap facility. It is part of our Ballistic Missile Defense Materials Characterization activity and here we are talking about pressures up in the megabar regime.

We are more than just a basic research laboratory, we also have production capabilities. An example of this is our metal-working activity. I feel it very important to our materials development mission that we are able to produce and fabricate materials, not just in small lab quantities, but in quantitits up to those approaching pilot scale so that the production processes then can be scaled up by industry. These prototyping capabilities include machining facilities. We get deeply involved in the manufacture of prototypes for various parts of the Army including most of the Development Commands, but in particular for the Armament Command, for whom we have made most of the prototypes of nuclear artillery projectiles in past years.

We are also active in the polymer and composite material processing technologies. For example, we have film stretching equipment for making stretched film armor materials such as XP polymer, injection molding equipment, and equipment for compounding and blending rubber. In fact, we are initiating a new coordinated program pulling together all of the scattered research and development work within DARCOM on rubber, and we will be using the compounding and blending operation in this effort.

A final example includes our filament winding, pultrusion, autoclaving and braiding facilities. These represent processing areas in the composites and polymers area which we feel will become more and more important in future Army systems. With the emphasis on weight saving, higher performance, survivability, and ballistic damage tolerance, I predict that composites will be the wave of the future in many Army systems. We are putting a substantial part of our program into this area, since we feel that this is the current growth area.

Again, welcome to the Boston area. We look forward to seeing you at AMMRC.

KEYNOTE ADDRESS
AVRADCOM RESEARCH IN HELICOPTER VIBRATIONS

Major General Story C. Stevens
Commander, U.S. Army Aviation
Research and Development Command
St. Louis, Missouri

Since the maiden flight in 1940 of the first Army helicopter pictured in Figure 1, the Army helicopter has encountered a multitude of vibration problems. These problems have decreased system productivity and increased life cycle costs. The following is a progress report on reducing helicopter vibrations.

Over the past 40 years, there has been significant progress in vibration reduction as indicated by Figure 2. This reduction was partly the result of innovative industry and government-sponsored research, and partly because of increasingly stringent Army specifications. Initial reductions were accomplished by gradual improvements in vibration design approaches along with trial-and-error airframe detuning.

Over the past two decades, improvements were achieved, for the most part, by add-on vibration control devices designed to reduce rotor vibratory loads and airframe vibrations. However, the weight of these devices has increased from approximately 2% of the payload to approximately 10% of the payload. As a result, mission payloads have been reduced.

Even though vibration levels have been lowered, numerous vibration-related problems still persist in the design of the modern helicopter. Today's vibration problems are more critical due to changes in overall mission requirements which include: nap-of-the earth and high speed flight, advanced weapons delivery, survivability, transportability, high reliability, and low maintenance. The problems that had to be overcome during recent development programs provided impetus to develop advanced vibration reduction methods. About five years ago, AVRADCOM's Research and Technology Laboratories responded to this need by emphasizing research efforts directed towards vibration analysis, vibration control and vibration testing.

Fig. 1 — First Army helicopter, Sikorsky R-4

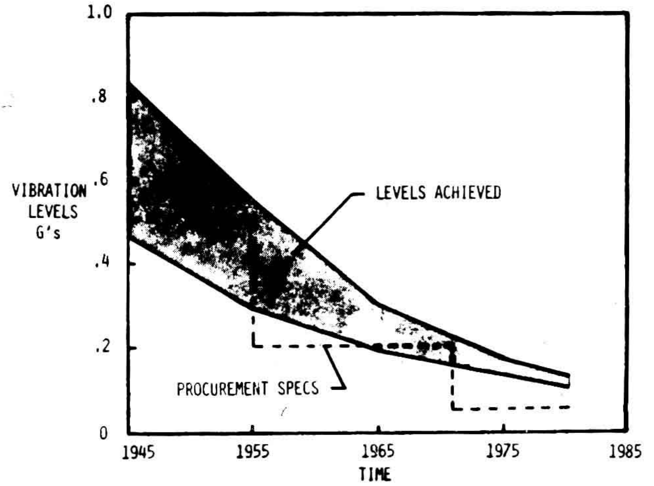

Fig. 2 — Trend of helicopter vibration levels

To put this research in perspective, we will consider: *first*, reviewing vibration design considerations which impact the modern Army helicopter; *second*, assessing vibration technology to establish research priorities; and *finally*, highlighting specific Army research programs which address major technology deficiencies.

The impact of high vibrations on helicopter design can best be described by recounting problems experienced during initial flight testing of the Army's newest helicopters. These helicopters are the UH-60 or Blackhawk, which is a utility helicopter, and the AH-64 or Apache, which is an attack helicopter, both of which are shown in Figure 3. The problems on these helicopters included higher than expected rotor vibratory loads, rotor/airframe interactions, airframe reasonances near excitation frequencies, high empennage vibrations and ineffective vibration control devices. As a result, vibration levels measured on the prototype aircraft were significantly above Army specifications throughout the flight regime. These first flight vibration levels for the Blackhawk, shown in Figure 4, are typical for recent development aircraft. For the Blackhawk and Apache, these vibrations were reduced, as indicated in Figure 5, after making numerous configuration changes which included raised rotors, aerodynamic fuselage fairings, modified hub absorbers, installed airframe aborbers, local stiffness changes, crew seat modifications, and isolated stabilators. Although these changes reduced vibration levels to within Army specifications, they still required substantial amounts of flight, ground and wind tunnel testing.

The configuration changes which were necessary to solve Blackhawk and Apache vibration problems impacted both system acquisition and productivity. The cost required to solve vibration problems during the development cycle is illustrated in Figure 6 in terms of engineering effort. During the design phase, effort increases gradually until first flight. At this point, an abrupt increase occurs that extends well into the development cycle. This increase can significantly delay helicopter delivery schedules. The payoffs for minimizing engineering effort and resulting schedule overruns are significant. In addition, operational costs have also increased due to higher weight penalties required to reduce vibrations.

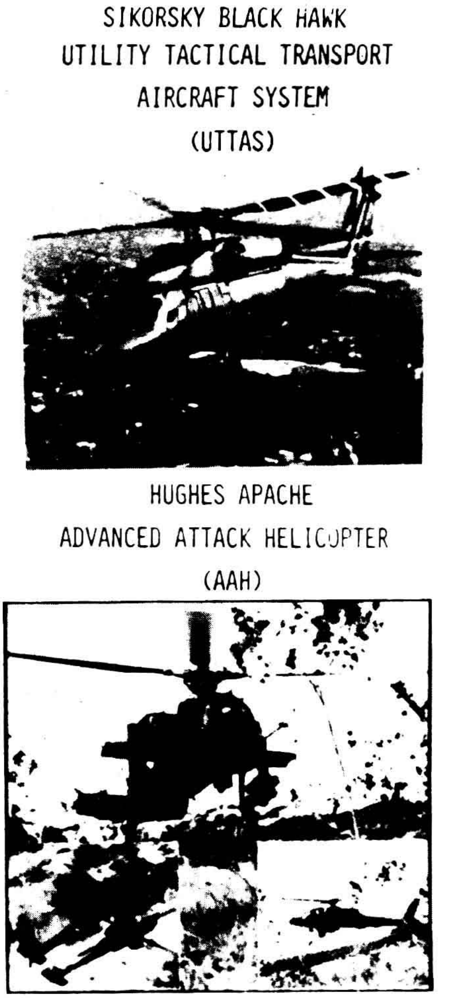

Fig. 3 — Modern Army helicopters

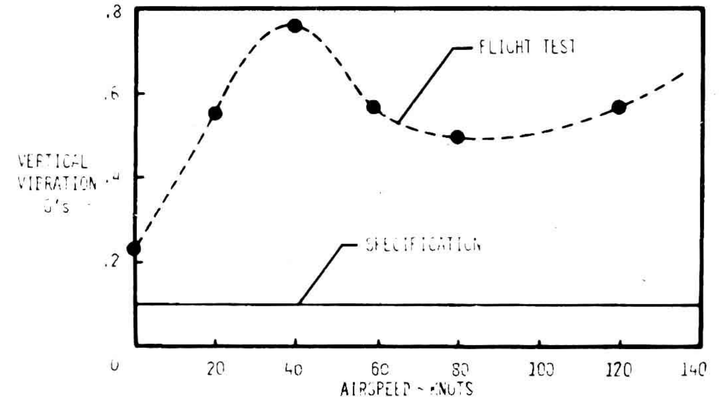

Fig. 4 — UTTAS prototype vibration levels

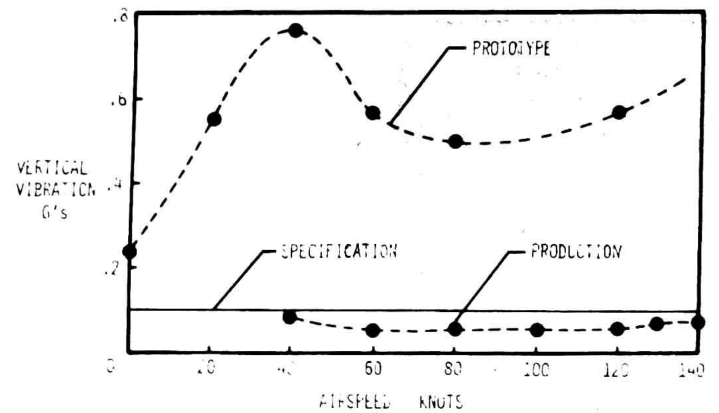

Fig. 5 — UTTAS prototype and production vibrations

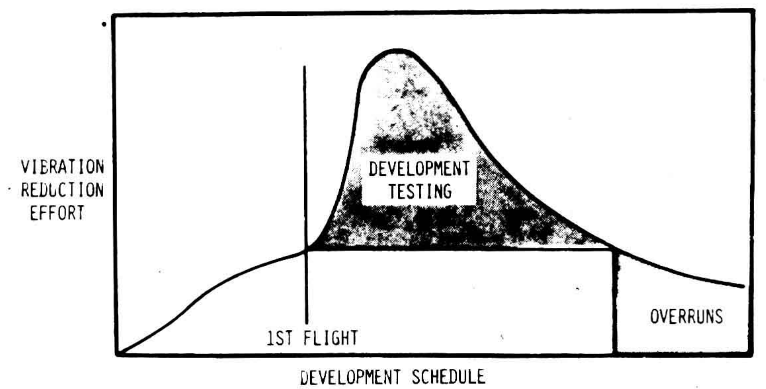

Fig. 6 — Vibrations impact system acquisition

Besides increasing costs during the development cycle, high vibrations can degrade overall helicopter productivity in several major areas. These areas include flight envelopes, human factors, structural integrity, reliability and maintainability, and transportability. A brief discussion of each of these areas follows.

In absolute terms, flight envelope limitations can be the most severe vibration penalties. The significance of forward speed on vibrations is shown in Figure 7. Vibration levels typically increased in the transition region around 30 to 40 knots followed by a decrease in the 80 to 90 knot region and rapidly increased for higher airspeeds. In aircraft developed in the 1950's, high vibrations sometimes limited forward speeds and degraded maneuverability. However, the Blackhawk and Apache were successfully designed to achieve mission profiles which were power rather than vibration limited. Nevertheless, even if power is available, helicopter forward speed and maneuverability are ultimately vibration limited as indicated in Figure 8.

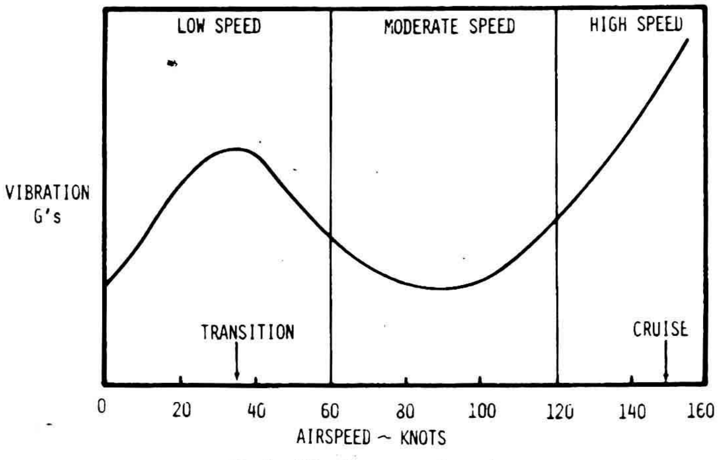

Fig. 7 — Vibration versus airspeed

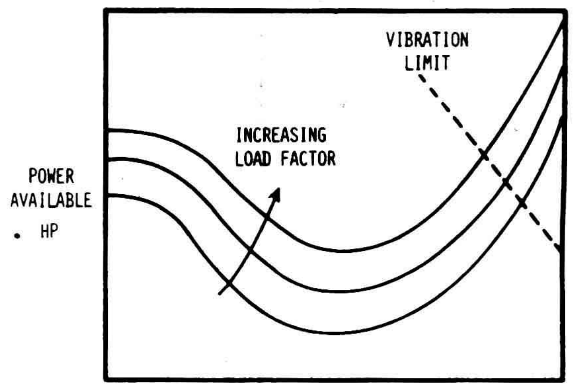

Fig. 8 — Vibrations limit flight envelopes

In the human factor area, adverse vibration and noise elements affect sensor perceptions (see Figure 9). Much of the human dynamic response data relates vibration amplitude and frequency to comfort and proficiency limits. These data show that high vibrations reduce performance and the ability to carry out complicated mental, tactile and visual acuity-related tasks. The trend towards complex displays and target designation systems places increased demands on these skills. Consequently, high vibrations degrade weapons delivery, especially in marginal weather and nap-of-the-earth operations. Over the years, lower vibration levels have increased human comfort and proficiency which improves crew mission effectiveness as noted in Figure 10.

High vibrations, or more specifically high vibratory stresses, affect the fatigue life and hence the structural integrity of both primary and secondary helicopter components. In fact, component fatigue margins have, in many cases, been reduced by high vibrations encountered during prototype flight testing. Of course, vibrations sustained in normal operations further reduce fatigue life margins. As a result, the operational life of helicopter components can be increased, as shown in Figure 11, by reducing vibrations.

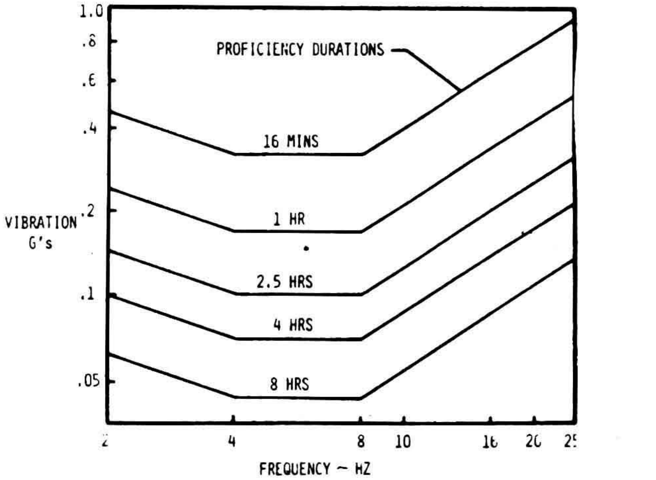

Fig. 9 — Human factors requirements

In addition to reducing operational life, excessive vibrations also reduce reliability and increase maintenance of airborne equipment. In Figure 12 you can see that there is a direct correlation between reduced failure rate and maintenance with reduced vibration levels. Failure rates associated with hydraulics, power trains, structures and

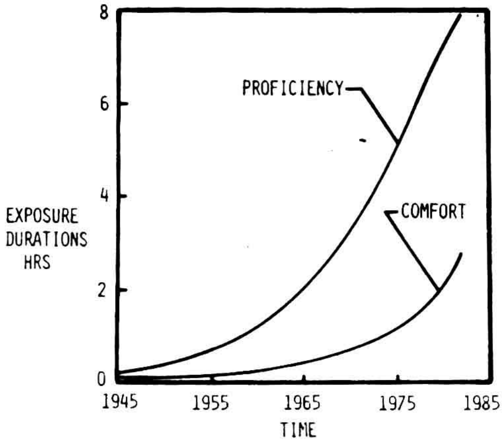

Fig. 10 — Human factors improvements

flight controls are related to frequency, amplitude and duration of the vibration environment. For example, Figure 13 shows that actuator failure rates are much lower in fixed-wing applications. The greater failure rate in helicopters can be attributed to higher vibration levels as well as high cycle usage. Although the connection may not be immediately obvious, vibrations and other factors affect helicopter transportability. For example, the Blackhawk and Apache procurement specifications required helicopter dimensions to be compatible with cargo compartments of military transport aircraft. The transportability requirement initially resulted in the main rotors being located close to the airframe. However, in this configuration rotor downwash caused higher than expected empennage vibrations and canopy drumming. These vibrations were so severe that they limited aircraft speed. Subsequently, main rotor to airframe separations were increased, as noted in Figure 14, to reduce vibrations at the expense of transportability.

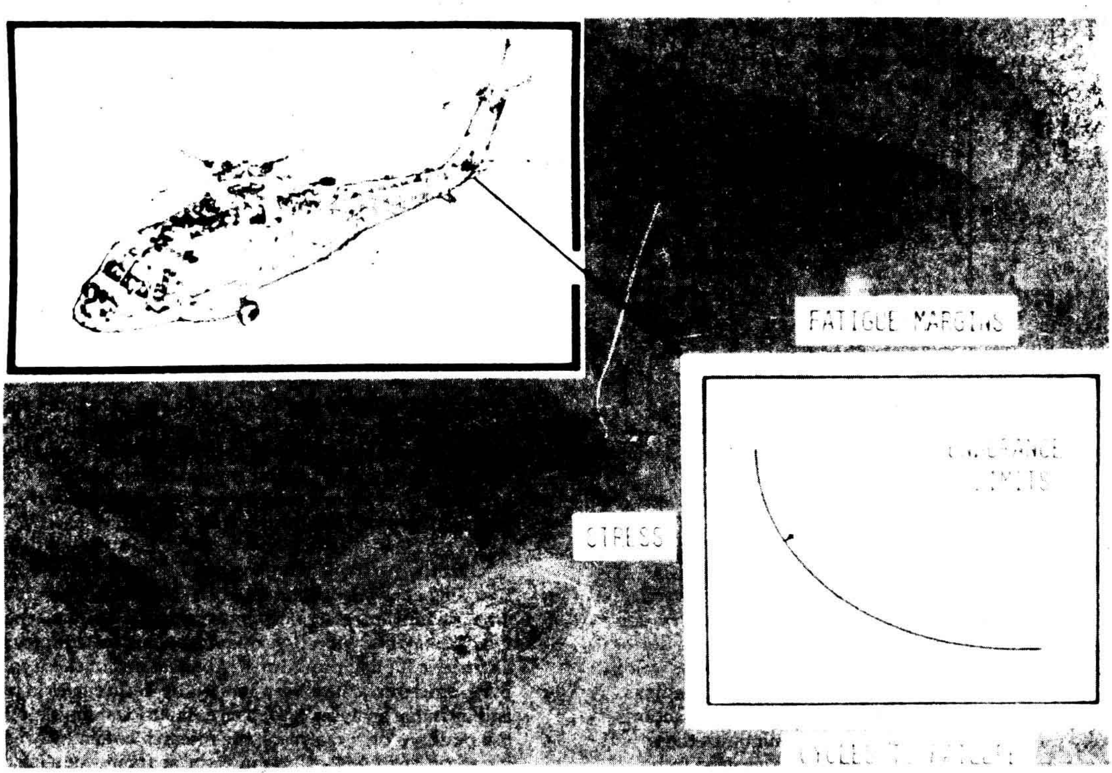

Fig. 11 — Structural integrity

The previous illustrations gave a perspective on the significance of vibrations during helicopter development. They underscored that high vibration levels affect a wide variety of helicopter design and operational features. Now, I would like to give you an assessment of where vibration technology stands.

Advanced vibration design technology has the potential to improve helicopter mission capabilities as well as eliminate costly trial-and-error development testing. To focus research on high payoff areas, AVRADCOM's Research and Technology Laboratories prepared a comprehensive Vibration Research Development Plan. This document reviewed past, current, and planned Army research programs; assessed the state of the art; identified significant vibration technology voids; and recommended areas for future research.

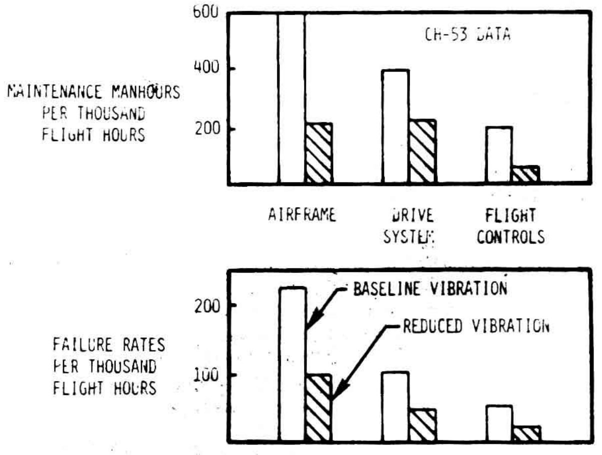

Fig. 12 — Vibrations versus R&M

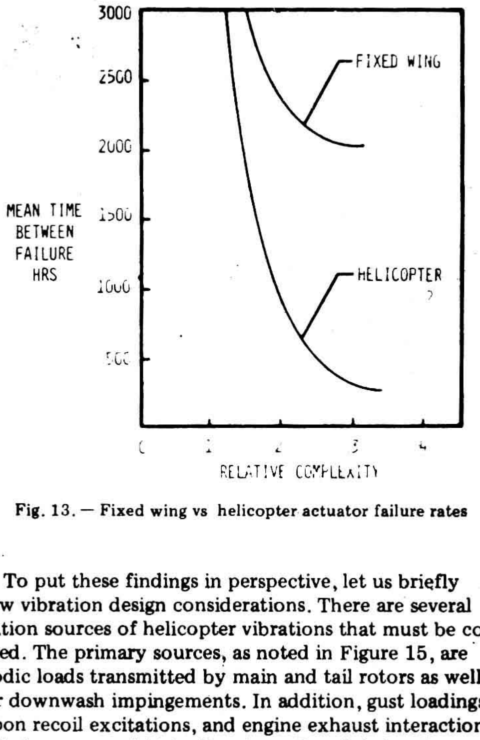

Fig. 13. — Fixed wing vs helicopter actuator failure rates

To put these findings in perspective, let us briefly review vibration design considerations. There are several exitation sources of helicopter vibrations that must be considered. The primary sources, as noted in Figure 15, are periodic loads transmitted by main and tail rotors as well as rotor downwash impingements. In addition, gust loadings, weapon recoil excitations, and engine exhaust interactions are likely sources of high vibrations. To minimize these vibrations, rotor and airframe configurations need to be designed as indicated in Figure 16. These configurations will yield low inherent vibrations. Then a variety of vibration control devices is available to further minimize vibrations at critical points. Consequently, the practical vibration solution usually combines passive vibration design and vibration control devices. Furthermore, vibration design strongly depends on an integrated testing methodology. The role of vibration testing is twofold. First, as noted in Figure 17, it provides a basis for verifying the vibration environment, and second, it supplements voids in existing analytical capabilities.

Based on the foregoing design considerations, five major categories of helicopter vibration research can be identified.

1. Rotor vibratory loads
2. Airframe structural dynamics
3. Rotor/Airframe coupling
4. Vibration control devices
5. Vibration testing

Each of these categories will be discussed in terms of technology deficiencies.

The first category, rotor vibratory loads, can be seen in Figure 18. Considerable research has concentrated on developing sophisticated rotor vibratory loads analyses. However, most of this research has focused on the basic disciplines of rotor aerodynamics and structural dynamics rather than on loads analyses. Hence, aerodynamic and structural phenomena intrinsic to rotor vibratory laods are still not completely understood and improvements in loads analyses have lagged those in these basic disciplines. Consequently, vibratory loads analyses are forced to rely on empiricisms and approximations. As a result, rotor loads predictions have not been very effective for detail design. In fact, these analytical deficiencies have required the designers to depend heavily on vibration control devices and trial-and-error testing.

In Figure 19 we see the next category, which is an airframe structural dynamic assessment. Helicopter airframes are complicated structures characterized by multiple cutouts, abrupt discontinuities and numerous dynamic components. Airframe analyses have evolved into applications of large-scale finite element models. Even with this advanced capability, helicopter designers have achieved only limited success in designing airframes with acceptable resonance placements. A significant deficiency has been an incomplete understanding of modeling requirements for complex helicopter structures. There has also been inadequate consideration of more design-respective finite element analysis programs. Thus, as with the rotor analyses, these sophisticated airframe analyses have not been very effective in the design process. Again, these deficiencies have led to a reliance of relatively heavy vibration control devices instead of passive design concepts.

Rotor/Airframe coupling is addressed in Figure 20. Coupling analyses depend on both structural dynamic and aerodynamic interfaces. Effective analysis and understanding of helicopter vibrations require sophisticated rotor/airframe coupling procedures. Applications of these coupling procedures have been limited by deficiencies in rotor and airframe analyses as well as computional limitations. In the past two or three years, the research community has increased analytical efforts in rotor/airframe coupling. This research has primarily addressed structural dynamic coupling aspects. Aerodynamic interactional vibration problems experienced during recent development programs provide ample evidence of existing voids in this area.

The fourth category of helicopter vibration research, as noted in Figure 21, is vibration control devices. The development of vibration control devices has been the dominant factor in reducing helicopter vibrations. These devices include main rotor hub absorbers, airframe absorbers, and transmission isolators. Local isolators have also been applied to crew seats, instrument panels, cabin floors and fuel tanks. There is a substantial level of effort within the Army and industry that focuses on minimum weight vibration control devices. More recently, active control concepts are being considered as alternatives to minimize rotor vibratory loads and reduce helicopter vibrations. The significant progress in vibration control warrants continued development of advanced concepts.

In the last research category, vibration testing, three major areas—ground and flight testing, wind tunnel testing, and human factors testing—have been assessed. These tests are frequently used to quantify flight loads and vibrations, to correlate and supplement analysis and to establish human vibration exposure criteria.

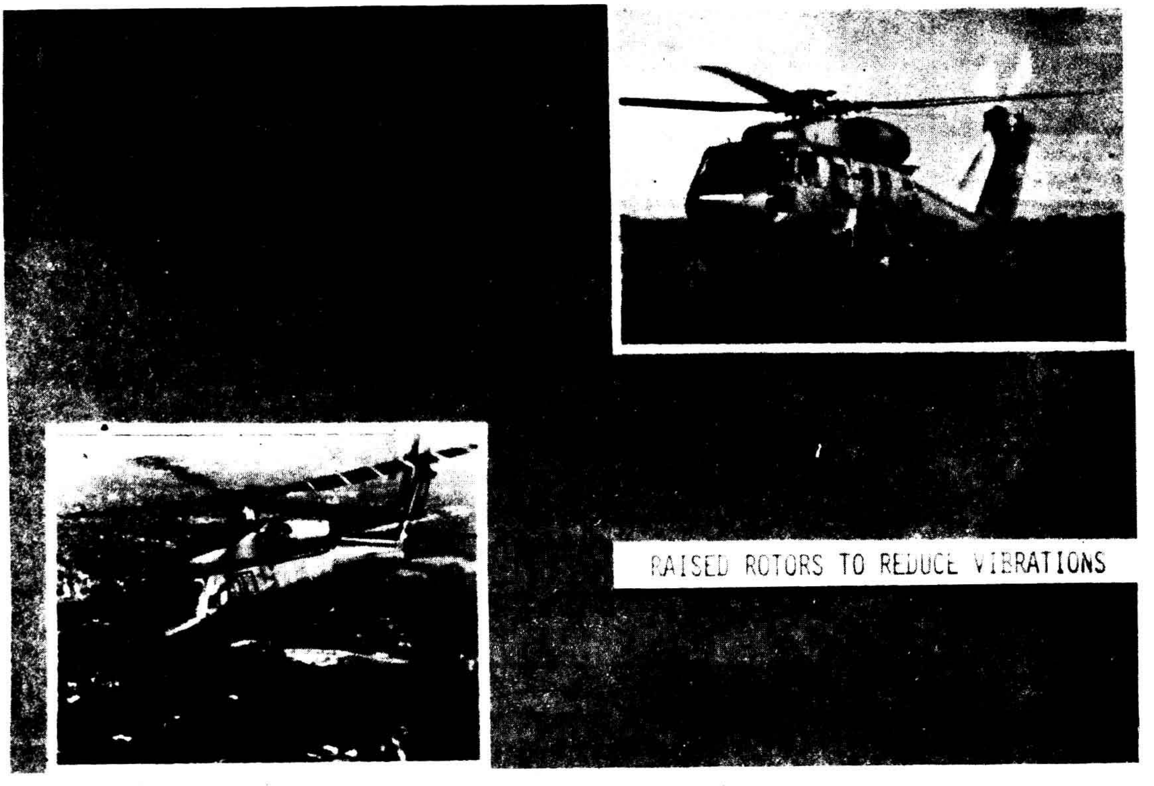

Fig. 14 — Transportability requirement

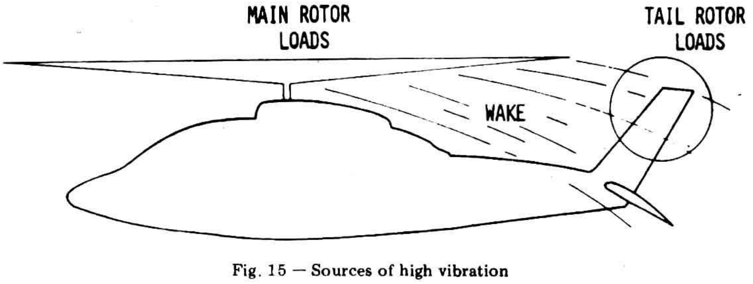

Fig. 15 — Sources of high vibration