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**RESEARCH REQUIREMENTS FOR DEVELOPMENT OF
ADVANCED-TECHNOLOGY HELICOPTER TRANSMISSIONS**

By

A. J. Lemanski

Prepared under Contract No. NAS1-13624

By

Boeing Vertol Company
Philadelphia, Pennsylvania

for

NASA

National Aeronautics and
Space Administration

December 1976

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By A. J. Lemanski

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ABSTRACT

This report contains the results of a study to identify those areas of improvement in helicopter drive-system technology which would result in the largest benefit in direct maintenance cost when applied to civil helicopters in the 1980 timeframe. A prototype baseline drive system based on 1975 technology provided the basis for comparison against the proposed advanced technology in order to determine the potential for each area recommended for improvement. A specific design example of an advanced-technology main transmission is presented to define improvements for maintainability, weight, producibility, reliability, noise, vibration, and diagnostics. Projections of the technology achievable in the 1980 timeframe are presented. Based on this data, the technologies with the highest payoff (lowest direct maintenance cost) for civil-helicopter drive systems are identified.

FORWARD

This report was prepared by the Boeing Vertol Company for the National Aeronautics and Space Administration, Langley Research Center, under NASA Contract NAS1-13624. William Snyder was technical monitor for this work. The Boeing Vertol Project Manager was Wayne Wiesner.

SUMMARY

Previous studies have shown that drive-system direct maintenance costs are 30 percent of helicopter direct maintenance costs. Since reduction in operating cost is a major goal for civil-helicopter improvement, the most effective way to reduce drive-system cost is to extend the average service life of the major components. Previous analysis indicates that an average life of 6,000 hours (on-condition removal) for the drive-system components can result in major reductions in life-cycle cost and direct maintenance cost. For the specific example cited, a 42-percent life-cycle cost reduction was estimated.

The results of literature search and previous studies indicate that the drive-system goal for reduction in operating cost is viable with a high probability of success by the application of the proposed advanced-technology features to an advanced-drive-system design concept. An example of the application of advanced-technology features to a typical helicopter transmission system design is presented along with their impact on individual-component design goals. Development programs for each technological area are discussed, along with planning estimates for cost and scheduled time for each major program task.

Previous independent research and development studies and contracted R&D studies have provided much of the background data for the work reported here.

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1.0 INTRODUCTION

This report presents the results of a study that was conducted to determine those areas of helicopter drive-system technology in which improvements would result in the largest benefit in direct maintenance cost when applied to civil helicopters in the 1980 timeframe. An outline and an estimated planning schedule for the research and demonstration of an advanced drive system are also presented.

Specific design examples of an advanced-technology and current baseline main-rotor transmission system are presented to define the improvement areas with respect to the selected baseline system.

The drive-system direct maintenance costs are 30 percent of helicopter direct maintenance costs, as shown in Figure 1. Reduction in operating cost is a major goal for civil-helicopter improvement.

The most effective way to reduce drive-system cost is to extend the average service life of major components (bearings, gears, splines, retention hardware, and lube-system components). Increased life will reduce spares procurement, maintenance, associated facilities, and labor. As shown in Figure 2, analysis indicates that an average transmission life of 6,000 hours (on-condition removal) in major subsystem components can result in a 42-percent life-cycle-cost reduction. Therefore, the specific goal is to develop a 6,000-hour average life in major subsystem components and achieve additional benefits as shown in Figure 3.

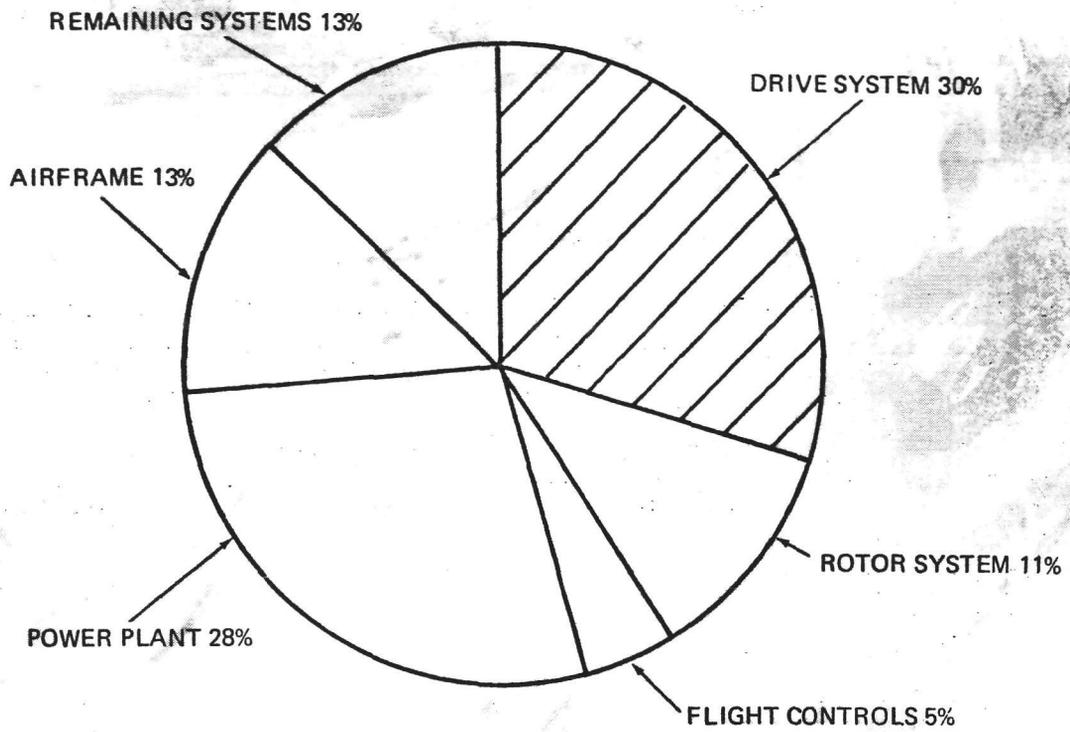
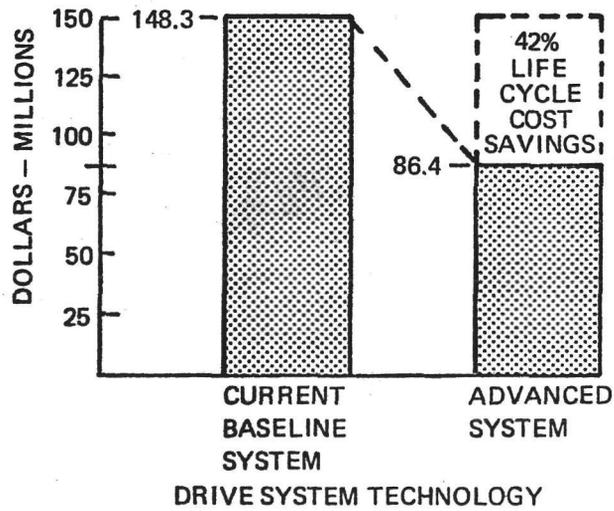


Figure 1. Drive-system direct-maintenance costs are 30 percent of total helicopter direct-maintenance costs



DRIVE SYSTEM TECHNOLOGY
 AIRCRAFT QUANTITY - 1,107 UTILIZATION - 50 FLIGHT HOURS/MONTH

Figure 2. Drive-system life-cycle cost comparison (1974 dollars)

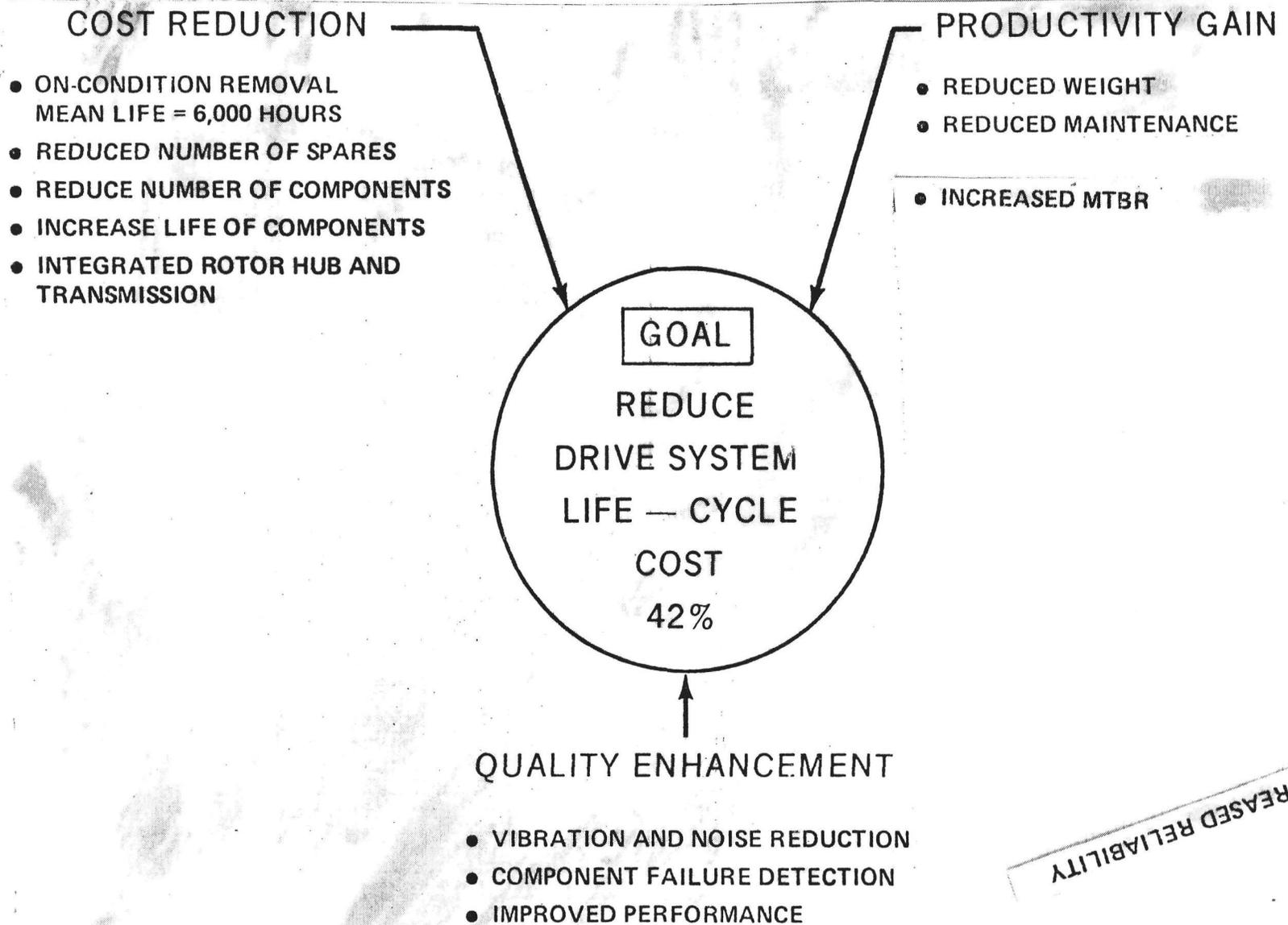


Figure 3. Drive-system program goal

2.0 BACKGROUND

The state of the art of helicopter transmission reliability is shown in Figure 4, which plots mean time between removal (MTBR) against the cumulative experience of the transmission. The reliability status of current technology is shown both with and without the present policy of fixed time removals (time between overhauls, TBO) and with more extensive development programs. Upper limits for current and advanced technology are suggested. To provide an approximation of the actual impact of these various MTBR levels, the number of removals and cost per year are shown corresponding to the MTBR scale. Assumptions used in this quantification are shown.

The nature of the reliability level at the point indicated in Figure 4 is examined further in subsequent discussions.

2.1 Current Technology

The present experience of helicopter main transmissions (representing current technology) is shown in Figure 5. A 900-hour MTBR for both scheduled and unscheduled reasons is the overall average, with TBO intervals of 1,100 to 2,000 hours. The unscheduled removals resolve to an MTBUR (mean time between unscheduled removals) of approximately 2,000 hours.

Transmission designs now under development are intended to operate without a TBO (on condition). With this situation the MTBR should be close to the MTBUR. Thus, the MTBUR of 2,000 hours is considered the baseline reliability and is examined in more detail in Figure 6.

Three groups of unscheduled removals are examined. The inherent failures constitute approximately 60 percent of the unscheduled removals. The remaining removals are split equally between those units removed through false indication of failure, inadequate diagnosis, or erroneous troubleshooting which do not have an actual functional discrepancy, and those which are removed due to real damage or suspected damage incurred because of a maintenance or operational action. The removals that could be addressed through basic design or technology are indicated.

Each of these groups is examined further. The inherent failures causing removals are shown in Figure 7 allocated to the primary component which failed.

Erroneous removals by their very nature cannot be assigned to components. The field-reported symptoms, however, do provide a clue as to the nature of the erroneous-removal problem. This distribution for CH-47 transmissions only is shown in Figure 8.

This display suggests that the majority of erroneous removals may be related to some problem or unusual condition within the assembly. The reason they were considered erroneous is usually that the criterion for removal was misinterpreted by maintenance personnel. Thus,

improvements in the basic reliability of the design can address a portion of these so-called erroneous removals. Furthermore, the components causing inherent failures may be contributing to these erroneous removals in a proportion similar to that shown in Figure 7. Of equal potential as the improvement in basic reliability is the benefit that improved diagnostic systems could have on reducing the frequency of erroneous removals. The improved application of existing diagnostic techniques such as oil-debris monitoring, as well as the use of advanced techniques, should both be considered as subjects for additional research.

The operations and maintenance-induced removals are distributed as shown in Figure 9.

Only the portion of damage during removal will be addressed by basic reliability improvements, although some improvements could be directed profitably at the damage during on-aircraft repair.

2.2 Current Technological Limit

The reliability growth experience shown in Figure 4 and the detailed causal factors shown in Figures 5 through 9 define the current technology. The frequency of these removals can be reduced in large production programs to a level that produces up to 6,000-hour MTBR's.

However, an integral element of this technological limit is the subtle but real tradeoffs that are performed between size, weight, costs, reliability, and maintainability. Particularly in helicopter transmissions, weight is an important design consideration and, unfortunately, often has a negative effect on reliability. The use of certain lightweight materials and the sizing of gears and bearings produce operating conditions (stresses, corrosion resistance, alignments, etc) which can be directly related to this reliability level.

The results of these types of design tradeoffs form a pattern for nearly all helicopter transmissions and may therefore be considered an inevitable consequence of rotary-wing design within the traditional emphasis on minimum weight and cost.

The specific impact on weight and cost as this emphasis is shifted toward reliability, maintainability, and general durability is not clearly evident. Additional research should be directed at this specific subject in order to identify the highest reliability possible with current technology within reasonable limits of cost and weight.

Most of these cost and weight penalties, however, can be avoided with the application of advanced technology. Following sections address these advancements.

2.3 Advanced Technology

The application of advanced technology to the design of helicopter transmissions will benefit reliability without imposing significant penalties of weight, maintainability, or cost.

* 4000 A/C at 30 HR/MT
 = 1,500,000 HRS/YR
 AT \$10,000/OVHL

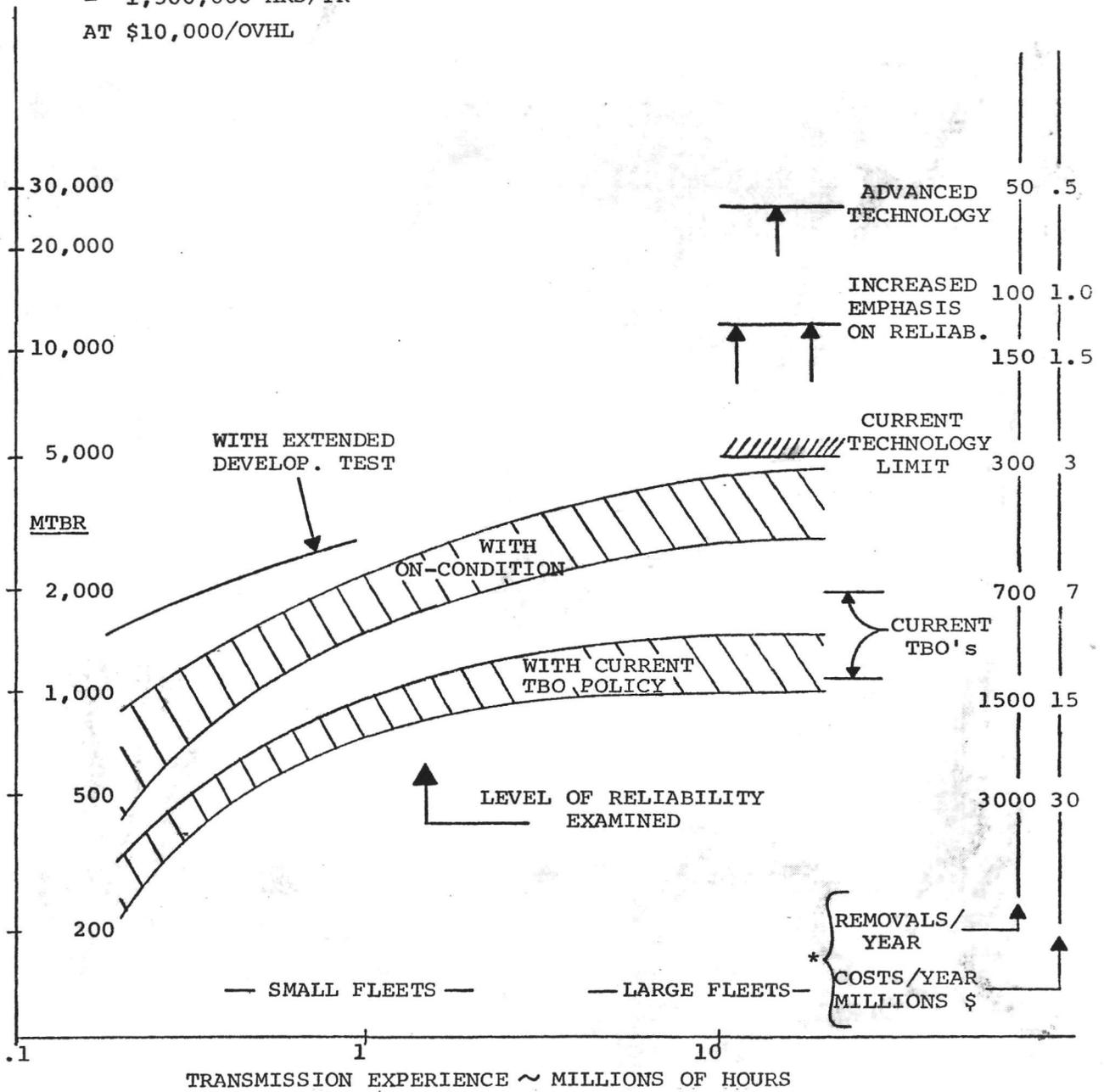


Figure 4. The state of the art of helicopter transmission reliability

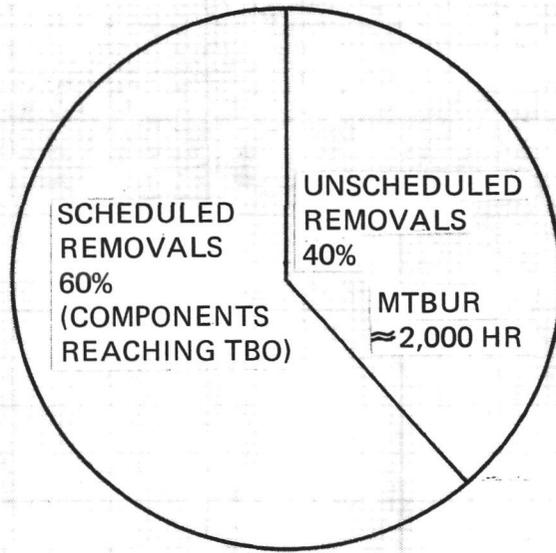


Figure 5. Causes of removals from present experience on current-technology transmissions with 900-hour MTBR's

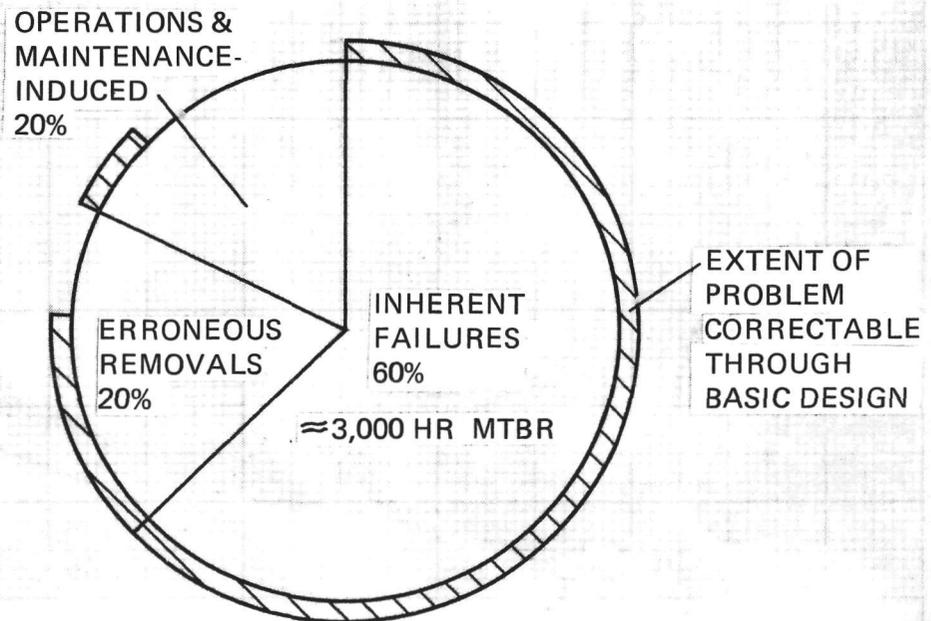


Figure 6. Causes of unscheduled removals of current-technology on-condition transmissions with 2,000-hour MTBR's

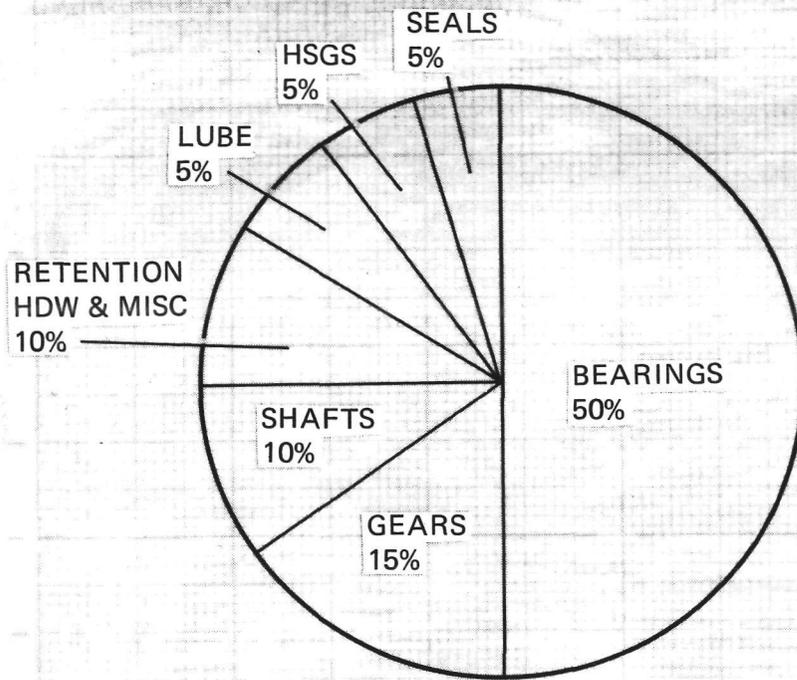


Figure 7. Component contribution to inherent failures causing removals

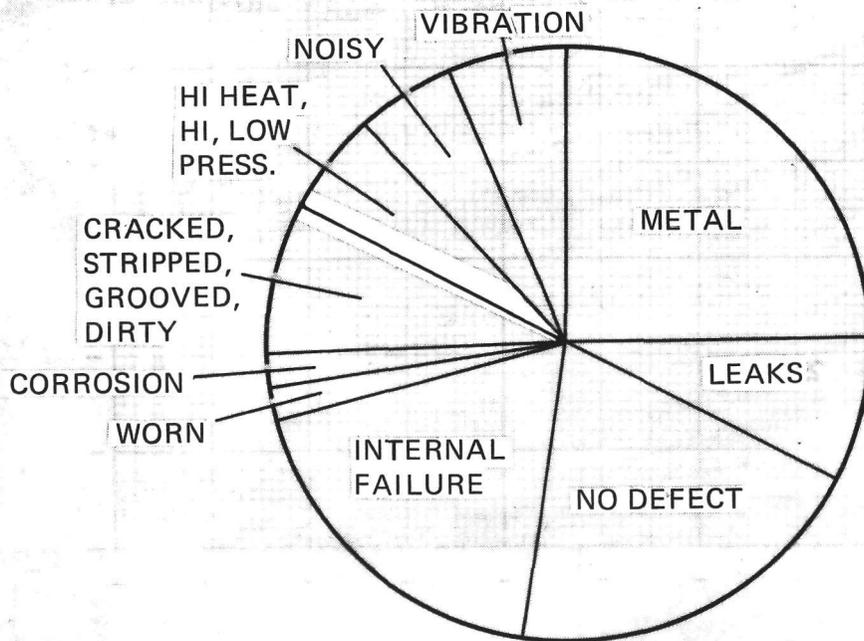


Figure 8. Transmission false-removal-symptom distribution

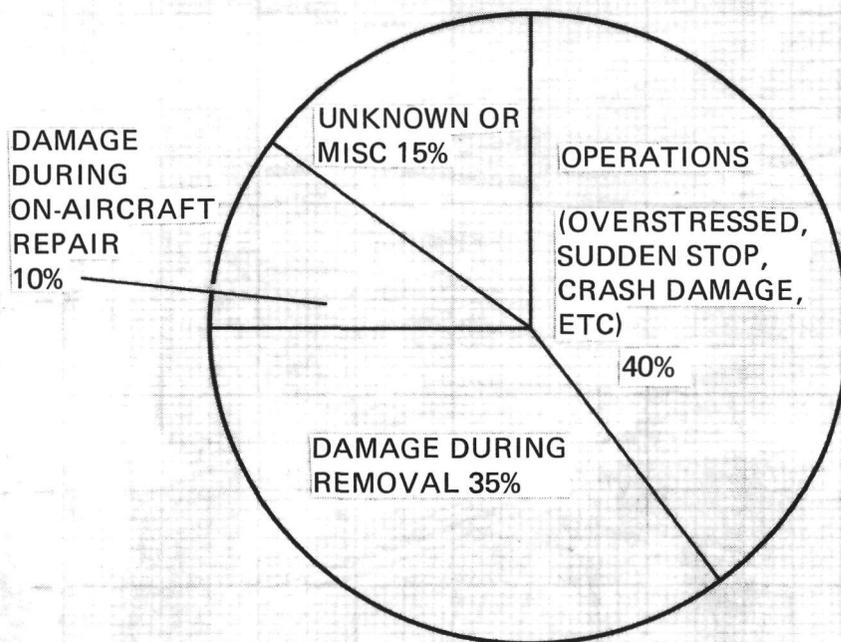


Figure 9. Types of operations and maintenance-caused removals

HYPHEN

3.0 APPLICATION OF ADVANCED TECHNOLOGY

The results of literature search and design studies indicate that the stated drive-system-program goal (Figure 3) of cost reduction, productivity gain, and quality enhancement is viable with a high probability of success by the application of the proposed advanced-technology features to an advanced-drive-system design.

An example of the application of advanced-technology features to a helicopter transmission-system design is presented along with their impact on the individual design goals.

3.1 Design Configuration

Contemporary transmissions have been designed with a swashplate above the planetary system; consequently, they require a relatively long rotor shaft. The advanced-technology transmission places the planetary system inside the swashplate ring, thereby permitting the hub to be an integral part of the final planetary-gear stage.

Recent rotor-head design advancements provide a greatly simplified configuration which facilitates integration with the main transmission. The advanced, bearingless rotor-head design eliminates all typical hub bearings; integration with the transmission improves reliability.

The advanced-technology transmission takes rotor loads through a direct path from the stationary planetary ring gear (which is an integral part of the housing) to the base-mounting support ring. This arrangement (Figures 10 and 11) decreases the length of the transmission-support arms by half, since they no longer have to clear the input shaft and swashplate actuators.

The proposed advanced-technology main-transmission system features a unique housing construction consisting of a lightweight, advanced graphite/polyimide composite material that provides improved stiffness over the contemporary magnesium housing, as shown in Figure 12. The advanced design eliminates the contemporary upper-cover structure (aluminum forging), resulting in a weight and cost reduction as shown in Figure 13. Furthermore, the material selected is inherently noncorrodible in the severe operating environment of the helicopter. The bevel-gear/bearing-system load reactions are taken through a stiffened, filament-wound, conical inner-spider support structure which is fabricated integrally with the outer-shell structure and base-support clevis fittings as shown in Figure 14.

Bevel-gear and support-bearing load capacity is improved due to material and configuration stiffness and shortened direct-load path. In contemporary designs the relatively thin magnesium-housing wall and internal support members react the bevel-gear/bearing loads; as a result, deflections do not permit development of optimum bevel-gear and bearing-load capacity.

This planetary system features a unique, single-stage, planet-carrier design which greatly reduces planet-post deflection and consequently improves gear and bearing life. The planet-gear output torque is taken through a circular plate located between the split face-width planet gears.

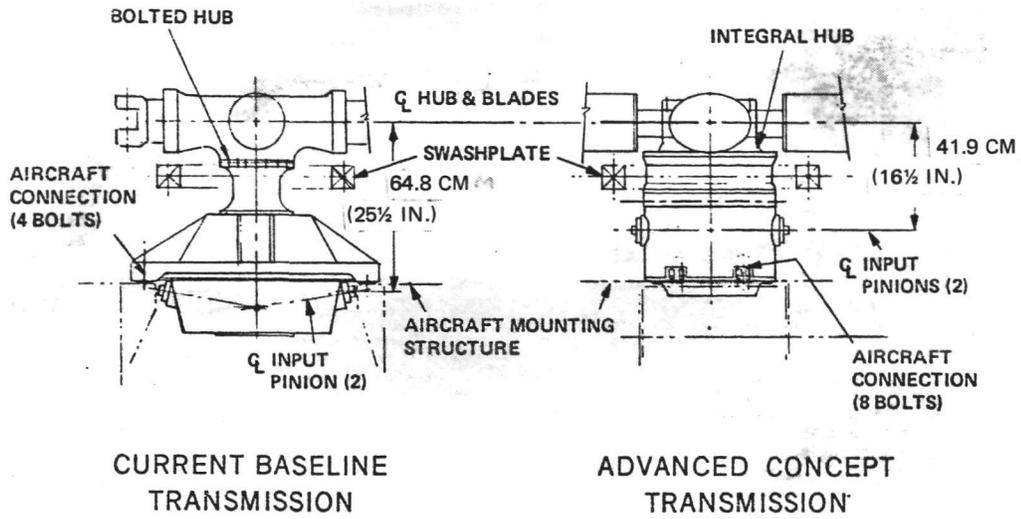


Figure 10. Comparison of profile views of main transmissions

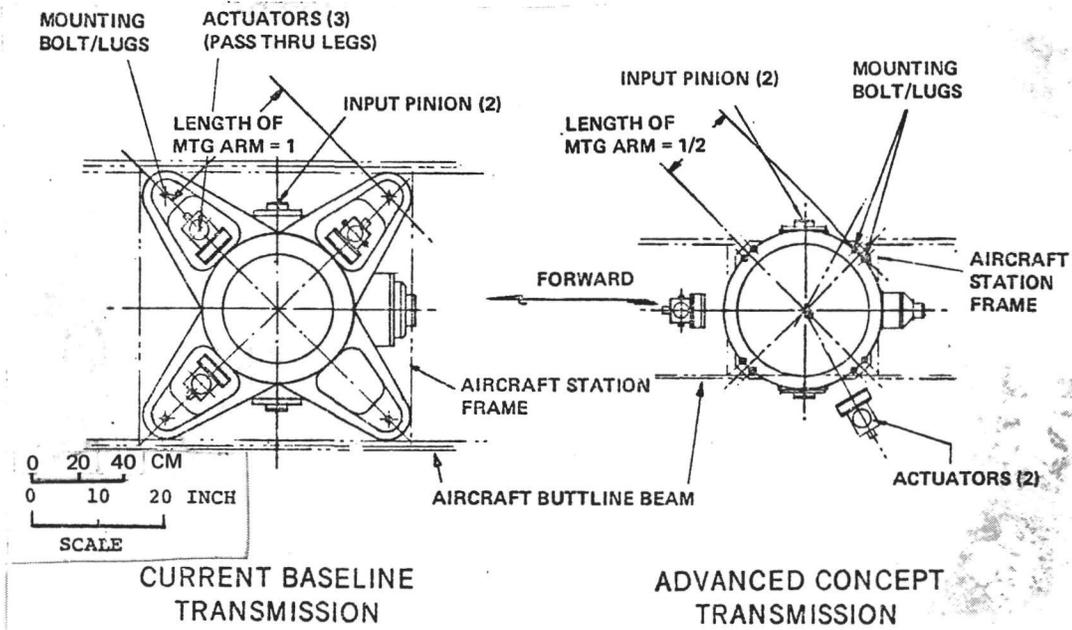


Figure 11. Comparison of plan views of main transmissions

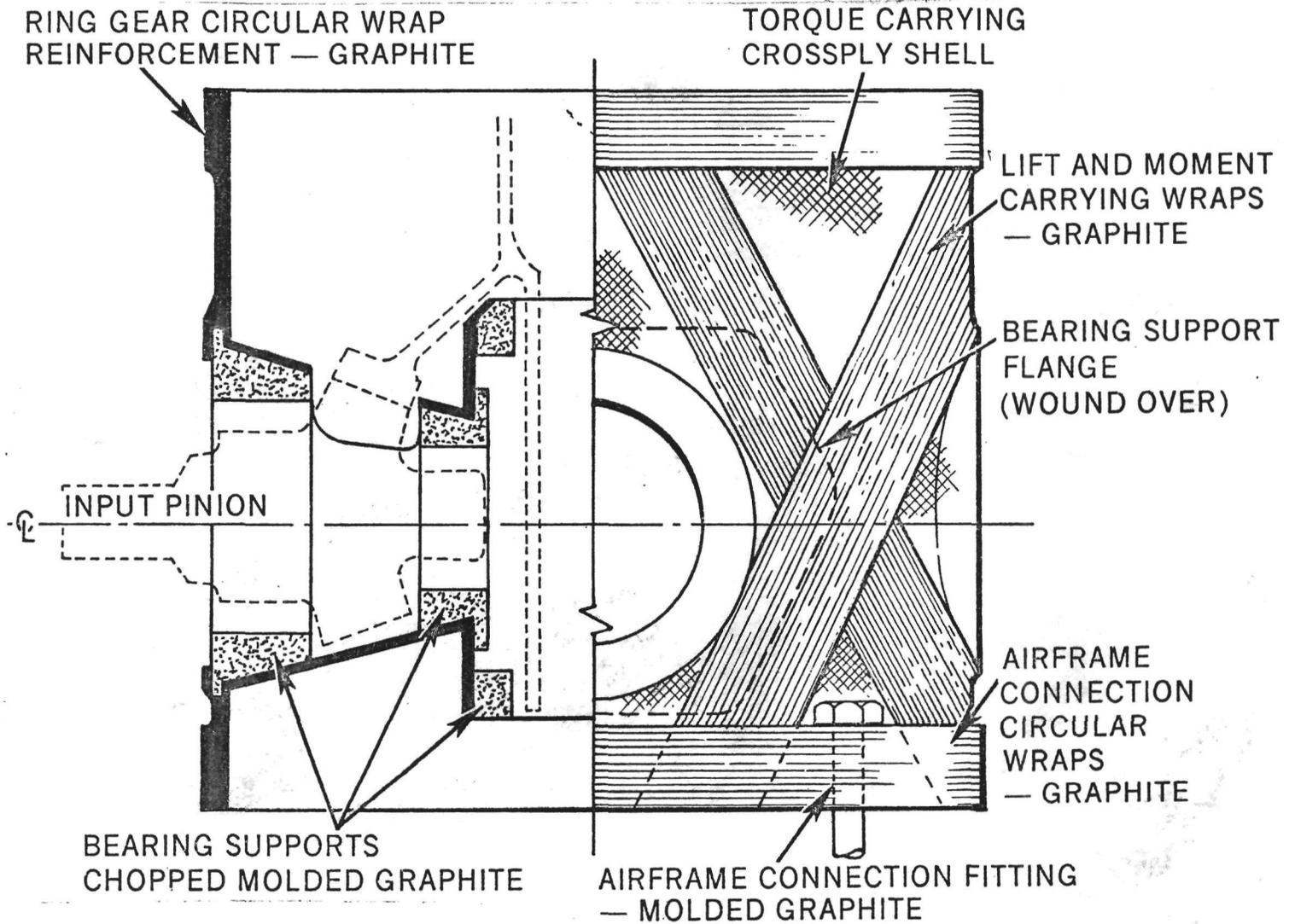


Figure 12. Graphite/polyimide composite housing

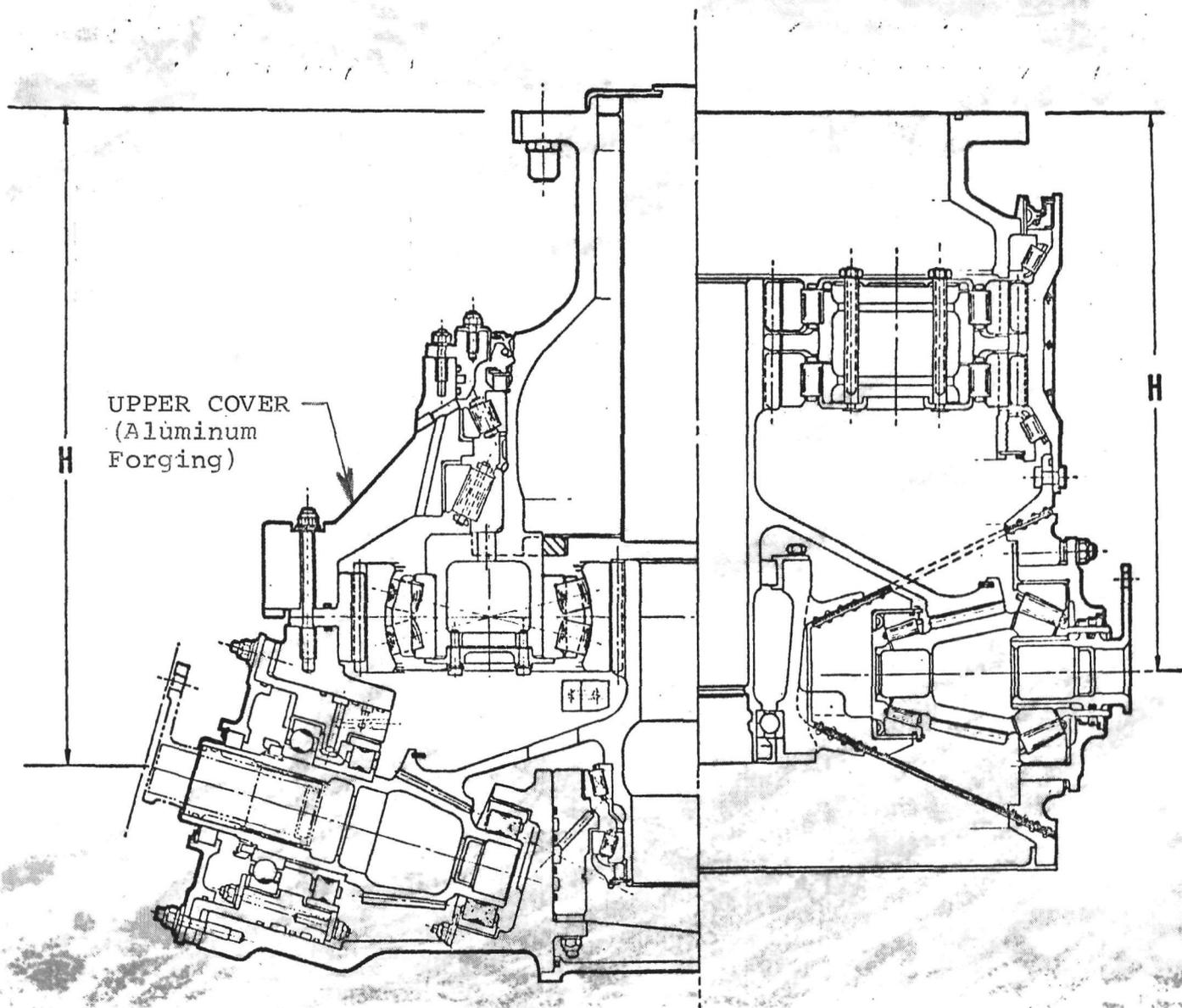


Figure 13. Comparison of cross-section views of main transmissions

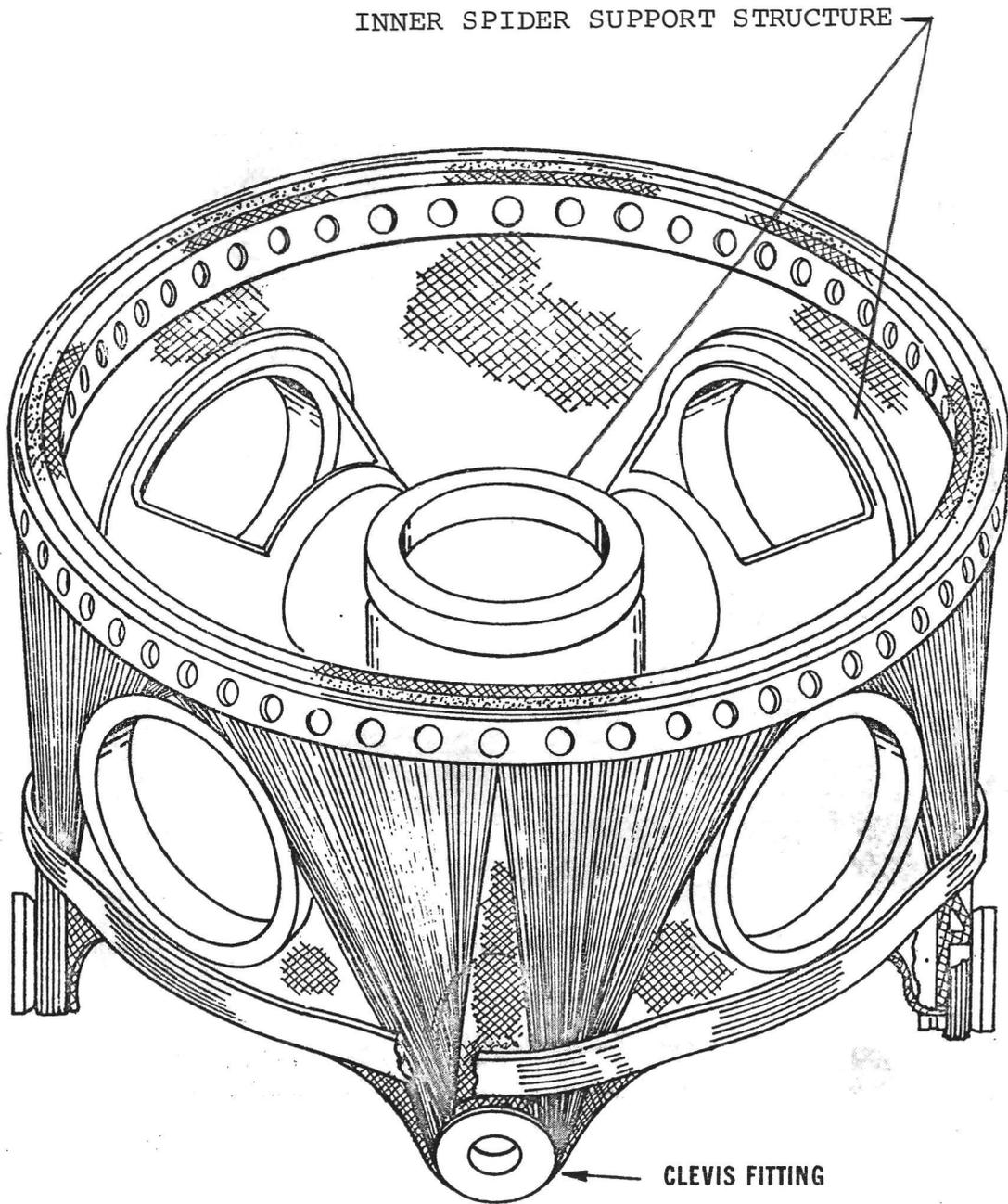


Figure 14. Inner-spider support structure of graphite/polyimide composite housing

This configuration reduces the planet-post height by half, placing the interposed carrier plate in equilibrium, and thereby reduces the influence of torque on gear-tooth and bearing alignment, as shown in Figure 15.

With the use of composite material for the carrier construction, an additional improvement in weight-to-stiffness ratio is possible. This feature can be traded against fabrication cost.

The planet gears will be supported by compliant cylindrical-roller bearings. This bearing system provides twice the life of the contemporary spherical-roller-bearing system, as shown in Figure 16. The advanced carrier design provides optimum operating conditions for compliant roller bearings due to the greatly reduced post deflections and housing deflections.

The planetary-gear teeth will be optimized for maximum load capacity and reliability through the use of noninvolute, high-contact-ratio tooth forms. This concept permits successful operation in the boundary-lubrication regime. This is possible because of the mating-profile curvatures; i.e., the profile shapes are tailored for optimum conformity and minimum sliding and surface heat generation.

An optimized and integrated spiral-bevel shaft and bearing system is featured in this advanced-transmission design. This unique configuration results in a reduction of three bearings and seven bearing races, including the rotor-shaft support. Integration of inner races with the shaft eliminates fretting and wear sites at the interface of the bearing and shaft. The design of the advanced tapered-roller bearing places the rib element on the stationary outer race, thereby improving the producibility of the integral shaft and bearing inner race. The tolerance to marginal lubrication is expected to improve due to oil delivery by centrifugal force directly to the roller-rib interface. This system improves the shaft stiffness by a factor of four in the radial direction.

Higher load capacity can be expected from the spiral-bevel gears due to improved alignment and uniform tooth-load distribution across the face.

3.2 Weight

Aircraft empty weight is directly related to lifting capacity and performance. Weight provides a common basis upon which rational decisions may be made regarding potential design tradeoffs. A weight reduction of 20 percent is projected for the application of advanced technology to helicopter transmissions. This will provide a margin for tradeoffs that may be required to reach reliability, maintainability, and producibility goals.

Specific weights for several existing helicopter transmissions are plotted in Figure 17. These weights include case/housings, bearings, seals, spacers, retainers, gears, planet-gear assembly, internal shafting, accessory drives, free-wheeling unit, gearbox supports, and complete lube system (including oil, plumbing, blower, and cooler). Considering a mean line through these points, the specific weight trend for contemporary helicopter-transmission designs is about 0.40 lb/hp. A projected 20-percent weight reduction will result in a specific weight of 0.32 lb/hp.

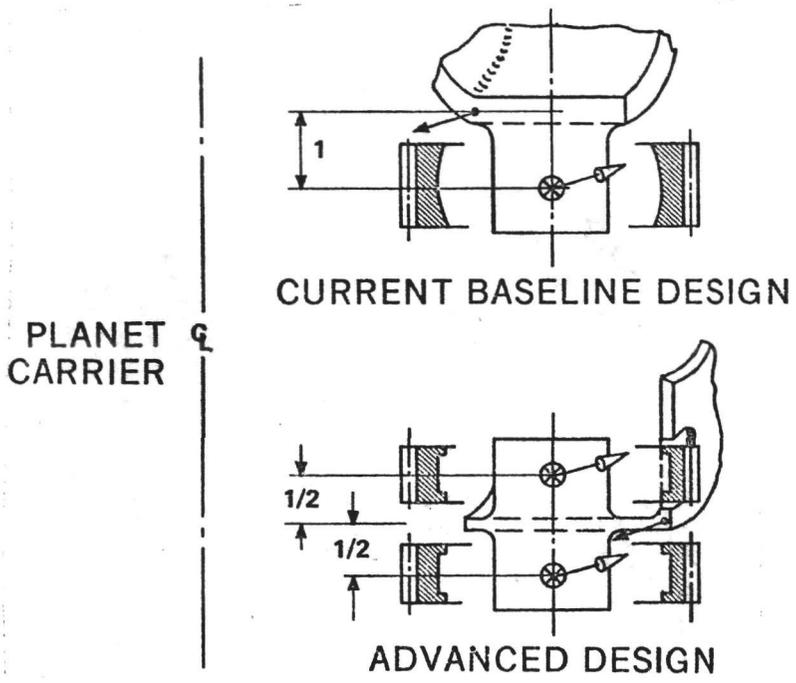


Figure 15. Planet-post height comparison

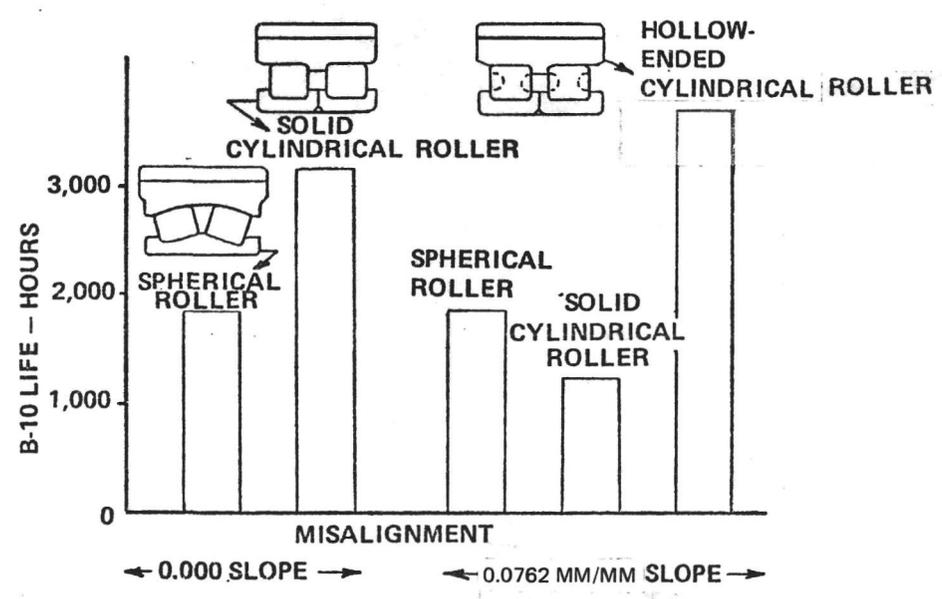


Figure 16. Planetary-roller-bearing life comparison

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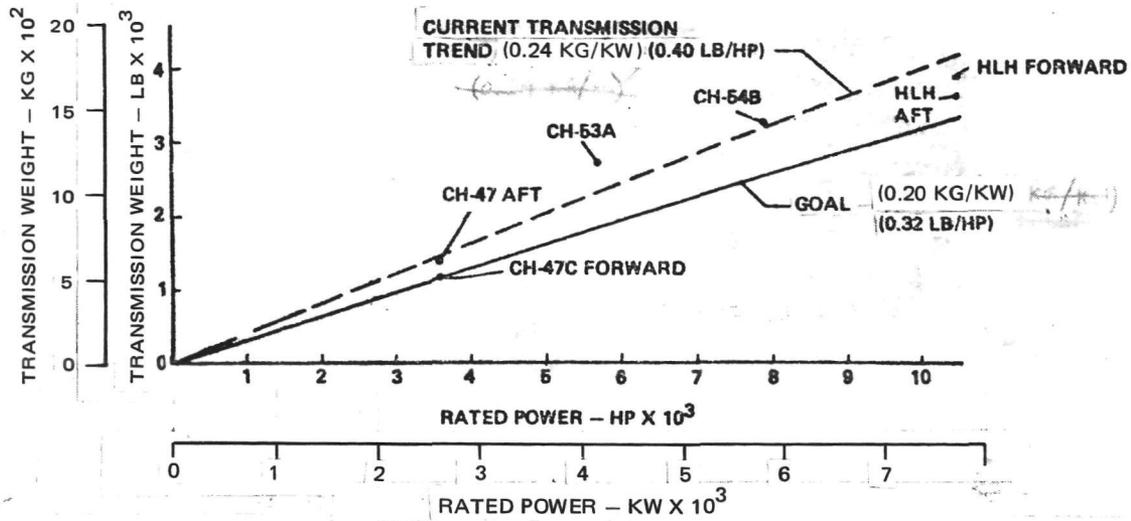


Figure 17. Specific weight of helicopter main transmissions

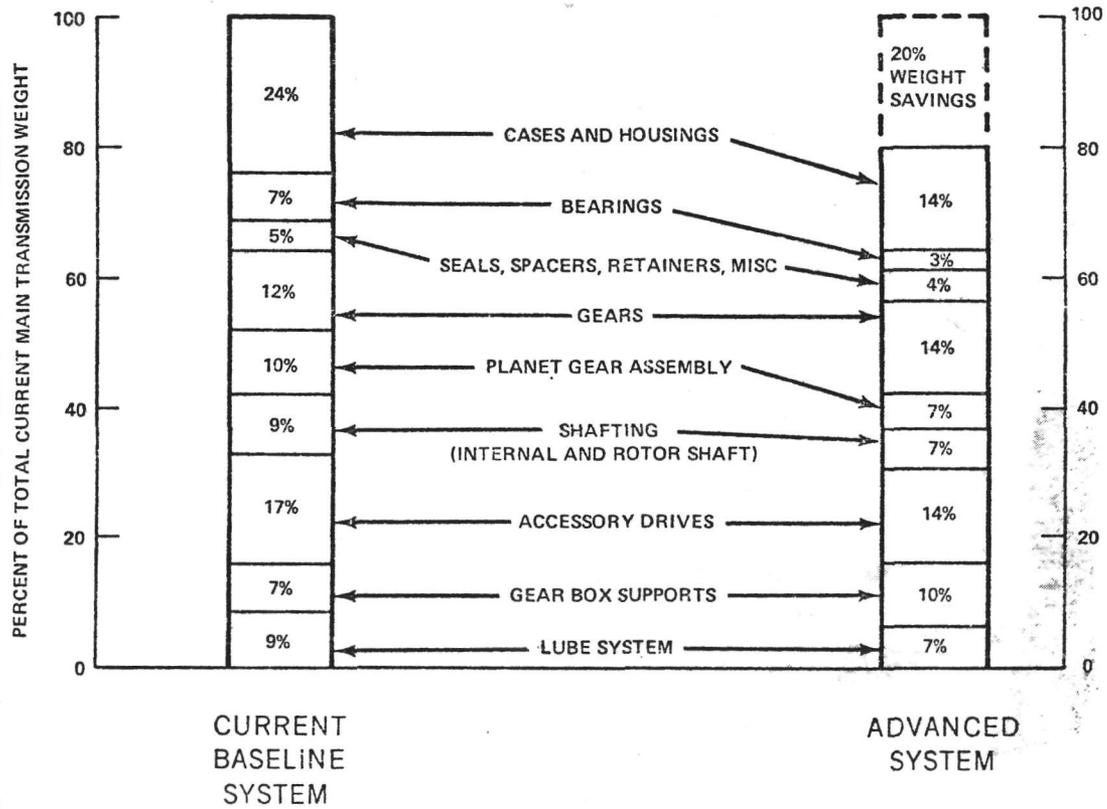


Figure 18. Transmission-component weight comparison

(0.003 IN./IN.)

The percentage of weight attributed to each of the major component groups is presented in Figure 18 for both the baseline and advanced system.

The following techniques were applied to reduced weight:

1. Arrangement that shortens the high-torque load path (Figure 19A).
2. Simplified design that minimizes size and number of parts (Figure 19B).
3. Application of high-strength, lightweight composite materials (Figure 19C).
4. Application of advanced base materials, surface treatments, coatings, finishes, and run-in conditioning (Figure 20).
5. Improved-technology components having greater inherent load capacity and life (Figure 21).

Other significant savings in weight were achieved in subassemblies and miscellaneous hardware. The savings were the result of simplified spiral-bevel-pinion designs that eliminated one bearing from each assembly, all fretting joints on the shaft, locknuts, threads, and other associated hardware including spacers, lubricator rings, and outer-race key retention, as shown in Figure 22.

3.3 Maintainability

The important facets of maintainability are:

1. Component condition-assessment and fault-isolation capability.
2. Inspection and servicing requirements.
3. Susceptibility to maintenance damage during installation, servicing, repair, or overhaul.
4. Accessibility of the component.

To achieve improvement in this area, false removals and maintenance damage must be minimized, if not eliminated.

Historically, many removals are due to inadequate diagnosis. Units are removed because of noises, vibrations, suspected unusual temperatures, etc, all using extremely subjective criteria. Even the standard diagnostic tool, oil debris (chip detectors, screens, and filters), requires personal judgment which often leads to assemblies being found in good condition upon teardown. There are design approaches which can make the design and diagnostics interface more effective. Specifically, simplified and stiffer housings and support structure can aid any of the vibration-oriented diagnostic techniques. A completely integral and simplified lubrication system also allows improved oil-debris methods to be employed. These requirements can be incorporated in an advanced-concept transmission system.

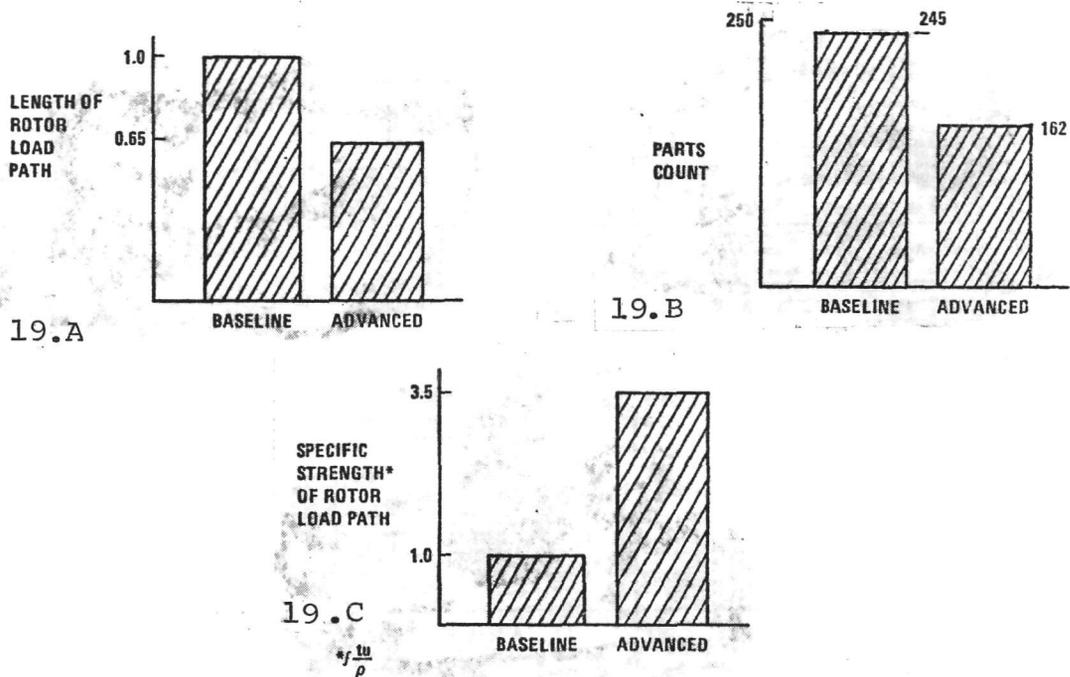


Figure 19. Comparison of transmission design characteristics

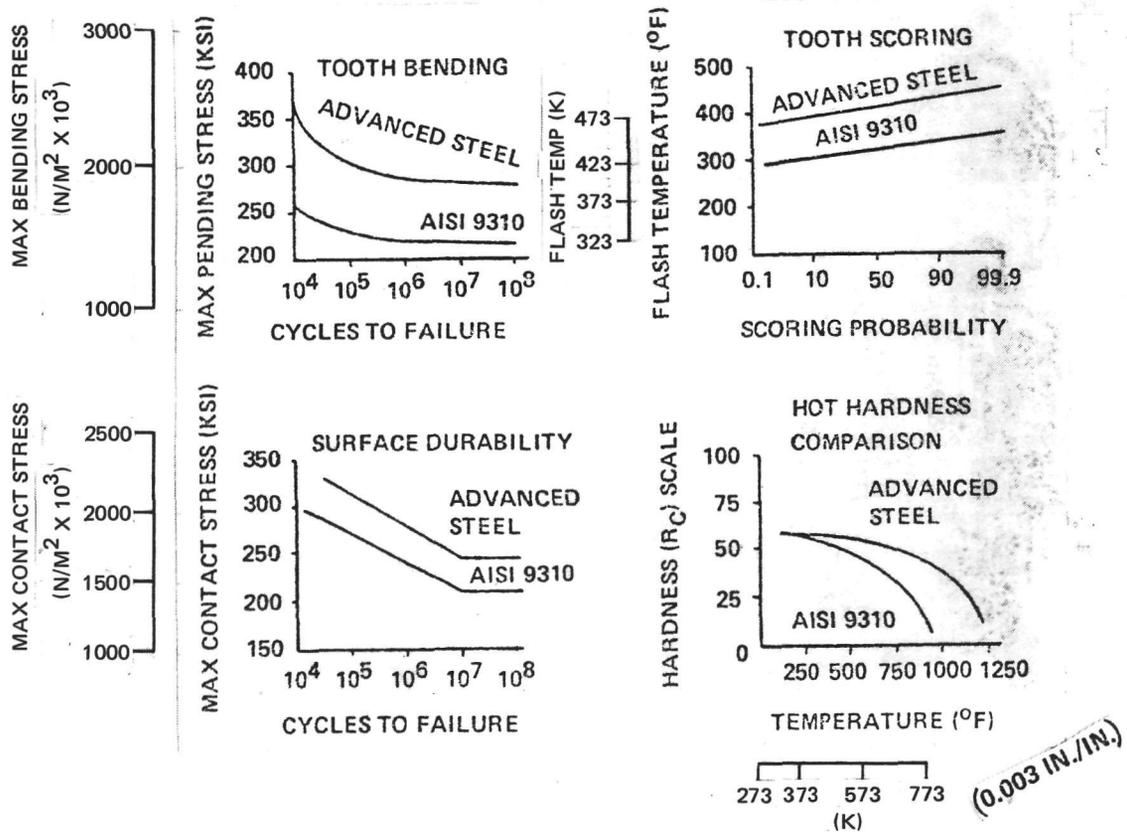
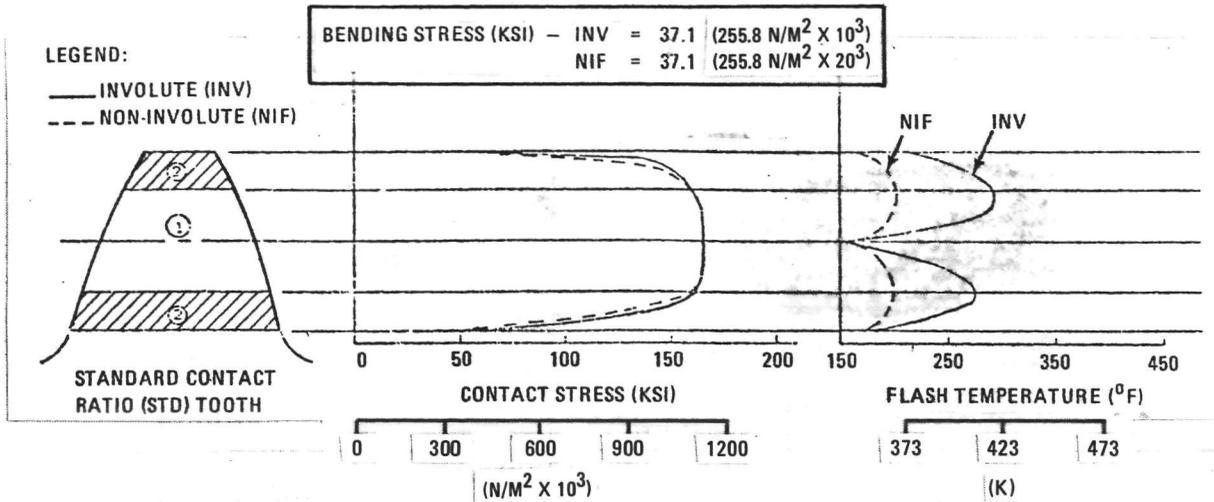


Figure 20. Comparison of advanced gear materials



NOTE: ENCIRCLED NUMBERS WITHIN TOOTH PROFILES DENOTE REGIONS OF LOAD SHARING BETWEEN 1, 2 OR 3 PAIRS OF TEETH.

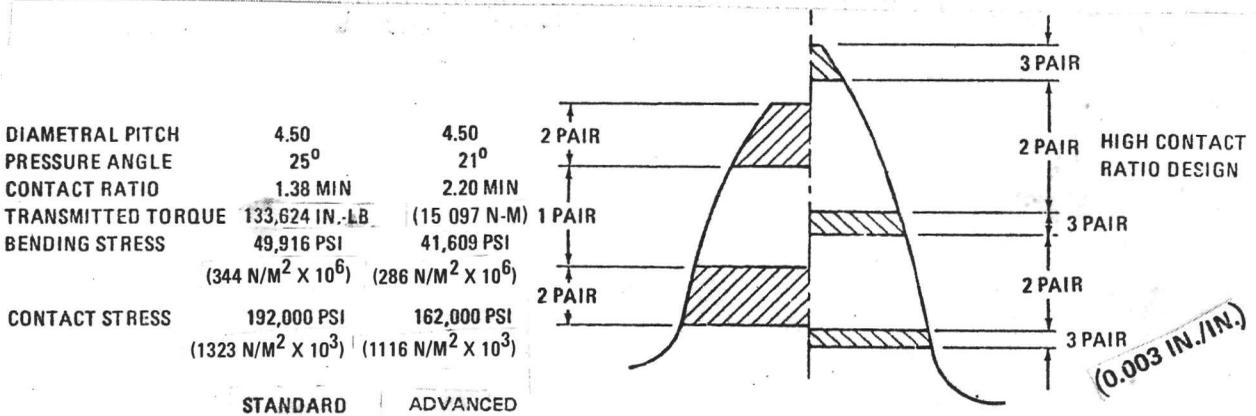
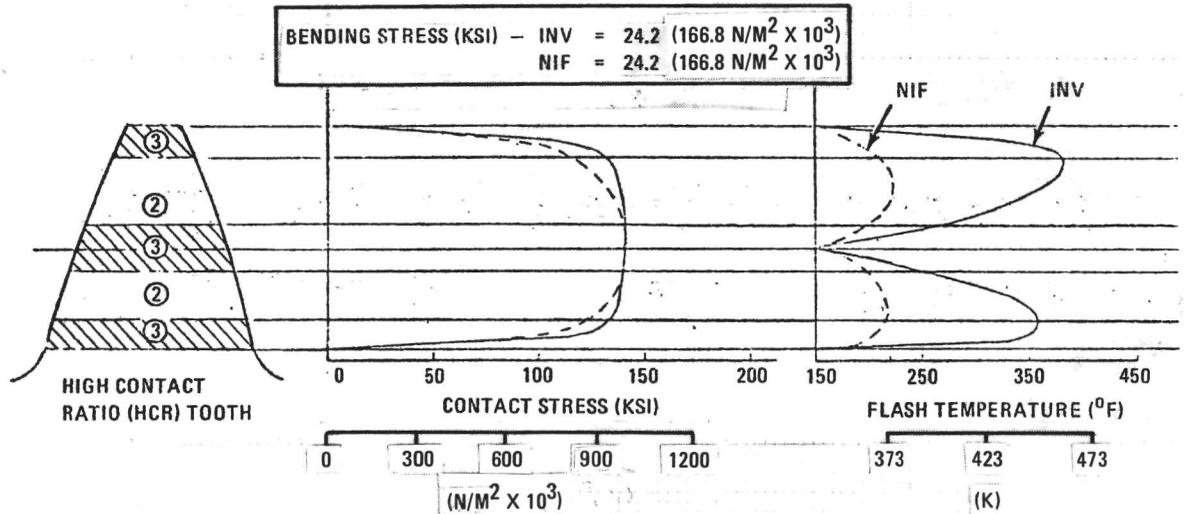
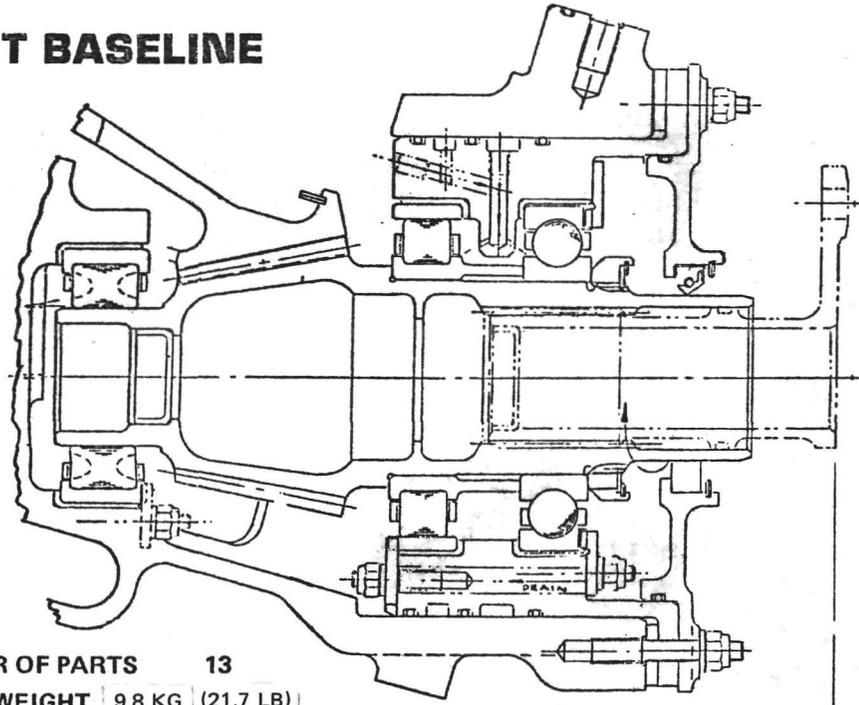


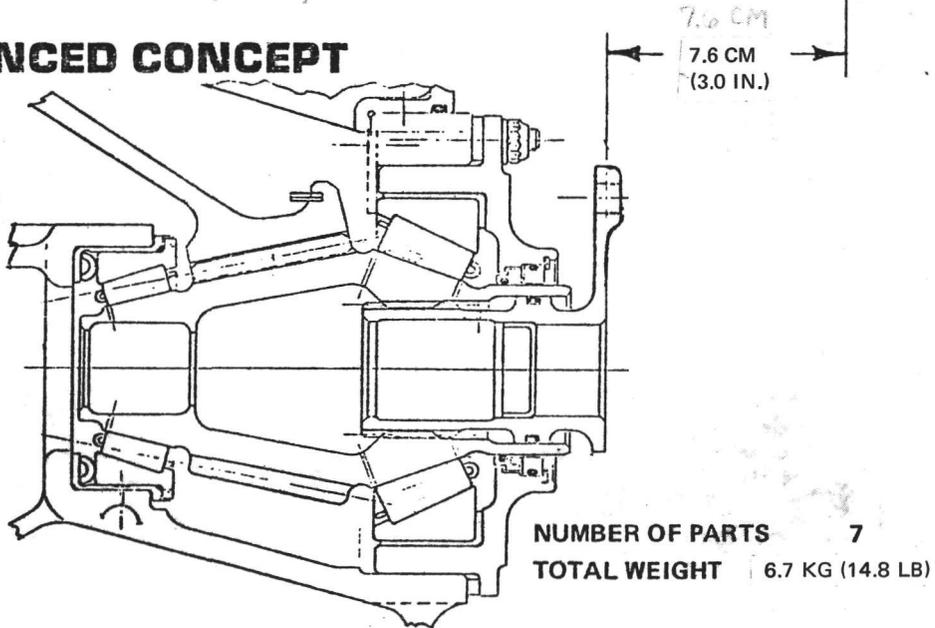
Figure 21. Comparison of involute and noninvolute tooth forms

CURRENT BASELINE



NUMBER OF PARTS 13
TOTAL WEIGHT 9.8 KG (21.7 LB)

ADVANCED CONCEPT



NUMBER OF PARTS 7
TOTAL WEIGHT 6.7 KG (14.8 LB)

Figure 22. Spiral-bevel pinion/bearing comparison

(0.003 IN./IN.)

Another major area of concern is the maintenance damage suffered by transmissions. This is manifested in external splines, connections to the housing (both for structural mounting and hardware attachment), and in exposed lubrication-distribution systems. External splines are eliminated where possible, or at least protected to a greater degree. Critical bolt connections will be self-indicating for correct torque. Accessibility to the main transmission is improved by the proposed arrangement, since input shaft and couplings, oil level, and all inspection and servicing points are above the torque deck. In addition, no external lube lines will be required, eliminating leakage points and sources of contamination.

3.4 Producibility

The major improvement foreseen in producibility is in new arrangements of components which lead to inherently simpler transmissions, the elimination of some components, and the integration of others. A review of piece-part costs in a typical contemporary transmission shows that a few large components account for the bulk of the costs (see Figure 23). Of the several hundred definable parts that constitute this assembly, seven alone account for 63 percent of the total cost. In order to realize a significant saving in recurring-production costs, these major components must have high priority in the design-innovation process. An advanced-concept transmission must address these components.

The distribution of costs within a main-rotor transmission is shown in Figure 24, which compares the 1960-era design to the advanced-technology concept. The areas of change include elimination of the shaft portion of the rotor shaft, integration of housing and upper cover into one unit, integral bearing races with gear shafts, and general simplifications in the assembly as a direct result of the new arrangement. These changes are estimated to provide a 20 percent reduction in cost of the assembly, even allowing for increased costs in certain areas such as the rotor-hub-support bearings. A further and equally significant saving is expected when the total effect of rotor-system and transmission integration is considered.

In addition to the basic advantages of arrangement, other areas of improvement include full integration of the lube-oil-cooling system into the main transmission, thus eliminating oil lines and connections, and elimination of bearing locknuts, shaft threads, and locking devices whenever possible through simplified gear mountings.

3.5 Reliability

A large majority of reliability problems arise from the lack of precision in our analytical methods for predicting the actual loads and material properties. These problems require a concentrated technical effort. Table 1 gives examples of the various kinds of reliability problems with the corresponding requirements for improvement. The contribution of these factors to CH-47 transmission reliability is shown in Figure 25, where the reasons for removal are segregated into categories of failures. It is apparent that the problems originating solely from conscious tradeoffs of reliability are a small percentage of the total. It is also apparent that the TBO limit caused unnecessary removal of many transmissions.

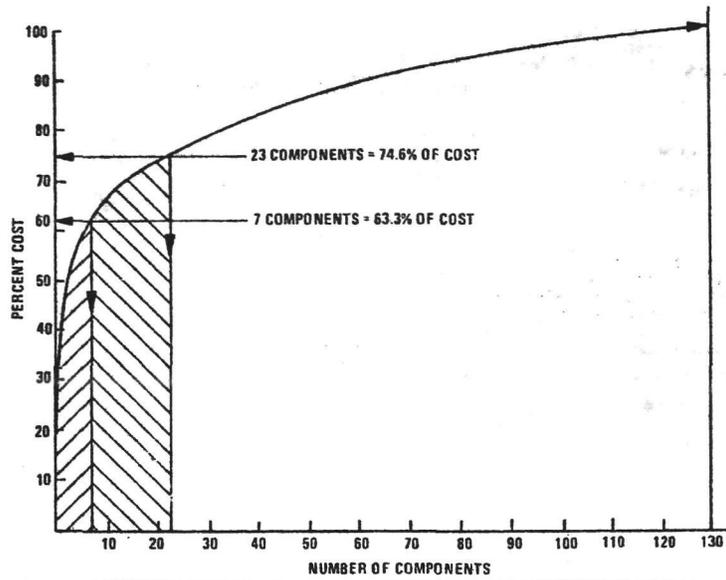


Figure 23. Transmission cost is driven by major components

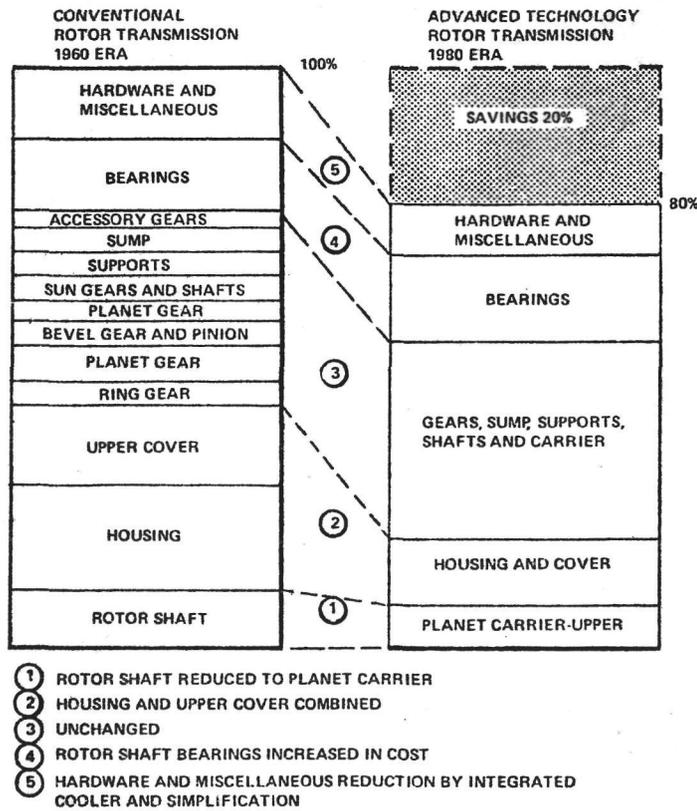
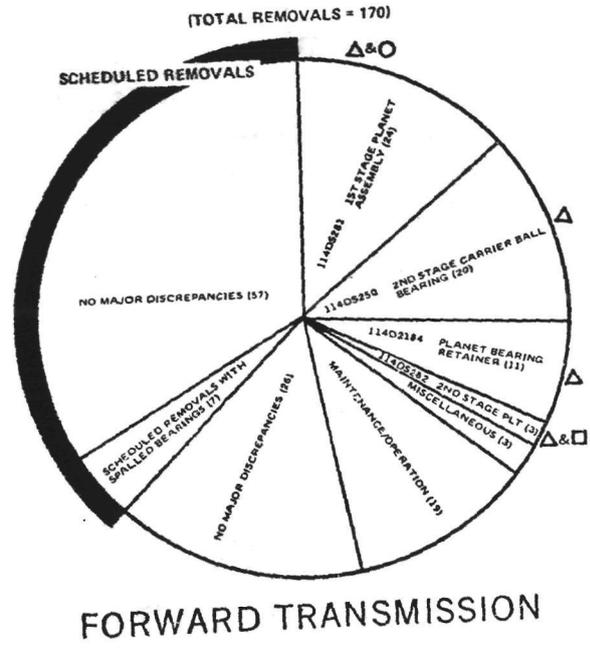
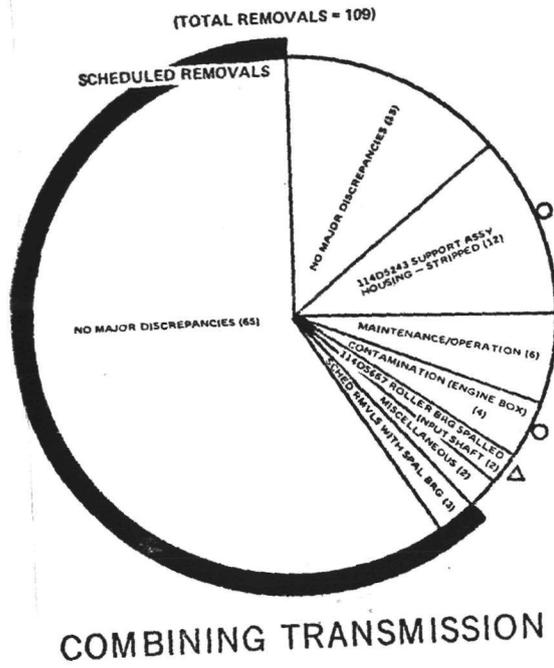


Figure 24. Comparison of costs (NI/NI £000)† dollars)

TABLE 1. TYPES OF TRANSMISSION RELIABILITY PROBLEMS

Types of Problems	Problems Due to		
	Design Shortcomings	Reliability Traded Off for Other Features (weight, cost, etc)	Unpredictable Loads or Material Properties
Bearings and Gears	Outer-race rotation Bearing-race spacer wear	Subsurface-initiated fatigue spalling Gear-tooth bending failures	Surface-initiated spalling due to edge loading, inadequate lubrication, debris effects, etc Cage wear or cracking Roller skidding Material inclusions or imperfections
Shafts and Splines	Spline external damage	Wear of soft splines not carburized and ground	Fretting-induced fatigue cracking of mounting surfaces Spline wear due to inadequate lube/misalignment
Retention Hardware, Housing, and Lubrication Systems	Locknuts backing off External case damage	Housing corrosion	Planet-bearing retainers cracking Lube-passage irregularities (walls too thin – cracking)
Corrective Action	Design criteria Simple designs	Customer requirements emphasizing reliability trade issues need to be quantifiable	Improved analytical methods Designs which produce more repeatable loads Simple designs

(NI/NI 800'0)



LEGEND:
 ○ = DESIGN EXECUTION
 □ = RELIABILITY TRADEOFF - ACTUAL POWER LIMIT
 △ = LOADS AND/OR MATERIAL PROPERTIES UNANTICIPATED

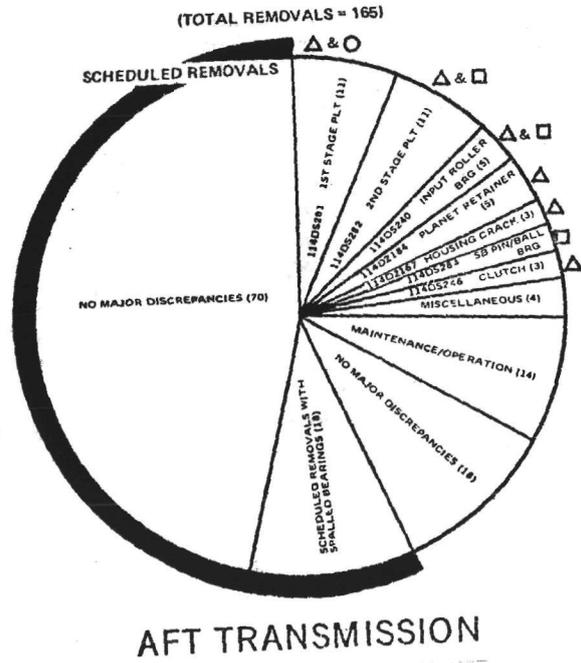


Figure 25. Reasons for removal of CH-47 transmissions

(NI/NI 800'D)

Nearly all helicopter transmissions now in operation have TBO levels in the range of 1,000 to 1,500 hours. Thus, regardless of their reliability, the MTBR's are limited to 900 to 1,300 hours. Figure 26 shows how a TBO interval limits total MTBR, as well as the range of current reliability levels (usually expressed as MTBUR – mean time between unscheduled removals). These reliability levels appear to be inherent to current designs. The TBO intervals, however, are not as clearly inherent to the design; criteria are now being developed to establish TBO intervals (or allow on-condition operation) on a more rational basis.

The reliability levels inherent to the latest generation of transmissions are not yet known. Design goals of 1,500-hour MTBR have been established for these units, and even higher values are expected once the development and maturity cycles are complete.

Thus, a 6,000-hour MTBR goal for the advanced-concept transmission translates into an on-condition maintenance concept (no TBO) and reliability (MTBUR) of 6,000 hours. If this 6,000-hour MTBUR is to include all causes of unscheduled removals, it is apparent that the frequency of actual component failures must be very small (see Figure 25).

Based on extensive analysis of reliability history, this will require design concepts which eliminate potential problems through two basic approaches. First, simplicity of design to avoid the opportunities for analytical errors or oversights during design and also to avoid manufacturing or assembly errors.

An advanced-concept transmission can incorporate simplified spiral-bevel input-pinion designs that eliminate one bearing, all fretting joints on the shaft, locknuts, threads, and other associated hardware including spacers, lubricator rings, and outer-race key retention.

Second, the design concepts must decrease the variability of loads that cause the majority of current problems. Specifically, a design that possesses stiffness of the housing and internal support structure significantly greater than current hardware could reduce the misalignments, deflections, and resultant load variations and thereby allow achievement of the reliability goals.

An advanced-concept-transmission design can incorporate a composite housing which could be optimized for increased stiffness and load-carrying capability for minimum weight. The use of advanced design techniques will permit improved stiffness and load-capacity features prior to initial fabrication. A composite housing will also eliminate corrosion and problems associated with internally cored lube passages.

A significant benefit can be achieved in helicopter drive-system life-cycle costs by the application of advanced technology as shown by the example in Table 2.

(NI/NI 0000)

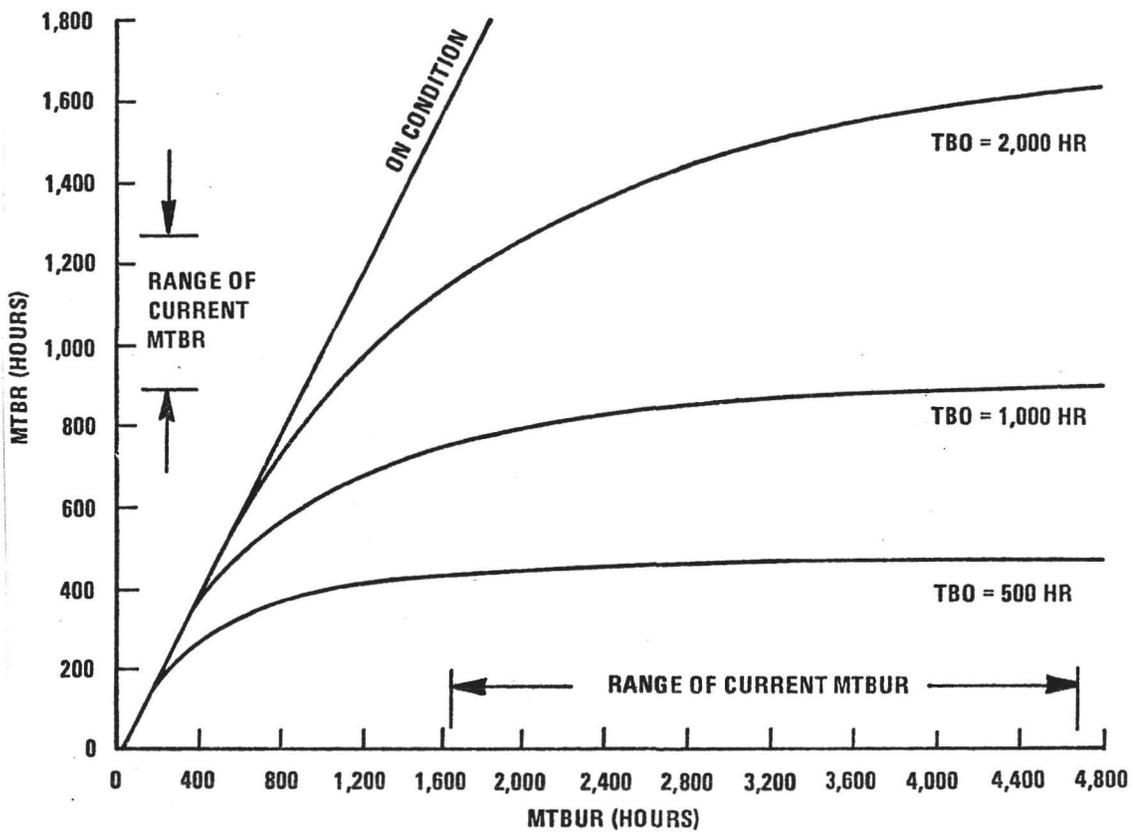


Figure 26. MTBR versus MTBUR for various TBO's

(NI/NI £00'0)

TABLE 2. DRIVE-SYSTEM LIFE-CYCLE COST COMPARISON

	Current Technology	Advanced Technology	Benefits
Number of Aircraft	1,107	1,107	-
On Condition - Mean Life (hr)	2,000	6,000	+4,000
Aircraft Set Cost (%)	100	81	-19
Overhaul Cost (%)	100	81	-19
Cumulative Flight Hours	3,786,420	3,786,420	-
Cumulative Overhauls	1,893	631	-1,262
Cumulative Aircraft Set Cost (%)	100	74	-26
Cumulative Overhaul Cost (%)	100	27	-73
System Cost/Flight Hour (\$)	39.00	23.00	-16.00
Total Benefit (Savings in 1974 dollars)			\$61.9 million

3.6 Noise and Vibration

Considerable attention has been focused in recent years on the reduction of noise levels of both military and civil helicopters. Helicopter noise emanates from three major sources: the rotor blades, engines, and transmissions.

The interior cabin noise is predominantly due to the transmissions (Figure 27), with the engines and rotors being secondary sources. Interior noise not only degrades crew performance by causing annoyance and fatigue, but also interferes with reliable communication and may cause hearing damage. Comfortable levels of interior noise are essential for passenger acceptance of civil helicopters.

By any of the numerous standards in existence for scaling annoyance and reactions to noise, transmission noise is particularly objectionable. Noise in excess of 120 decibels has been measured for the transmission of a medium transport helicopter which, for comparison, approaches the noise level of an air-raid siren. Not only is this noise level high, but its frequency typically falls within the sensitive 1,000 to 5,000-Hz range which is particularly annoying to the human ear (Figure 28). Furthermore, the pure (NI/NI 800) content, which results in a high-pitched whine, is subjectively much more annoying than broadband noise (Figure 29).

TWIN ENGINE RATING - 4474 kW AT 245 RPM
(6000 HP)

SINGLE ENGINE RATING - 2796 kW
(3750 HP)

GROSS WEIGHT - 20866 kg
(46,000 LB)

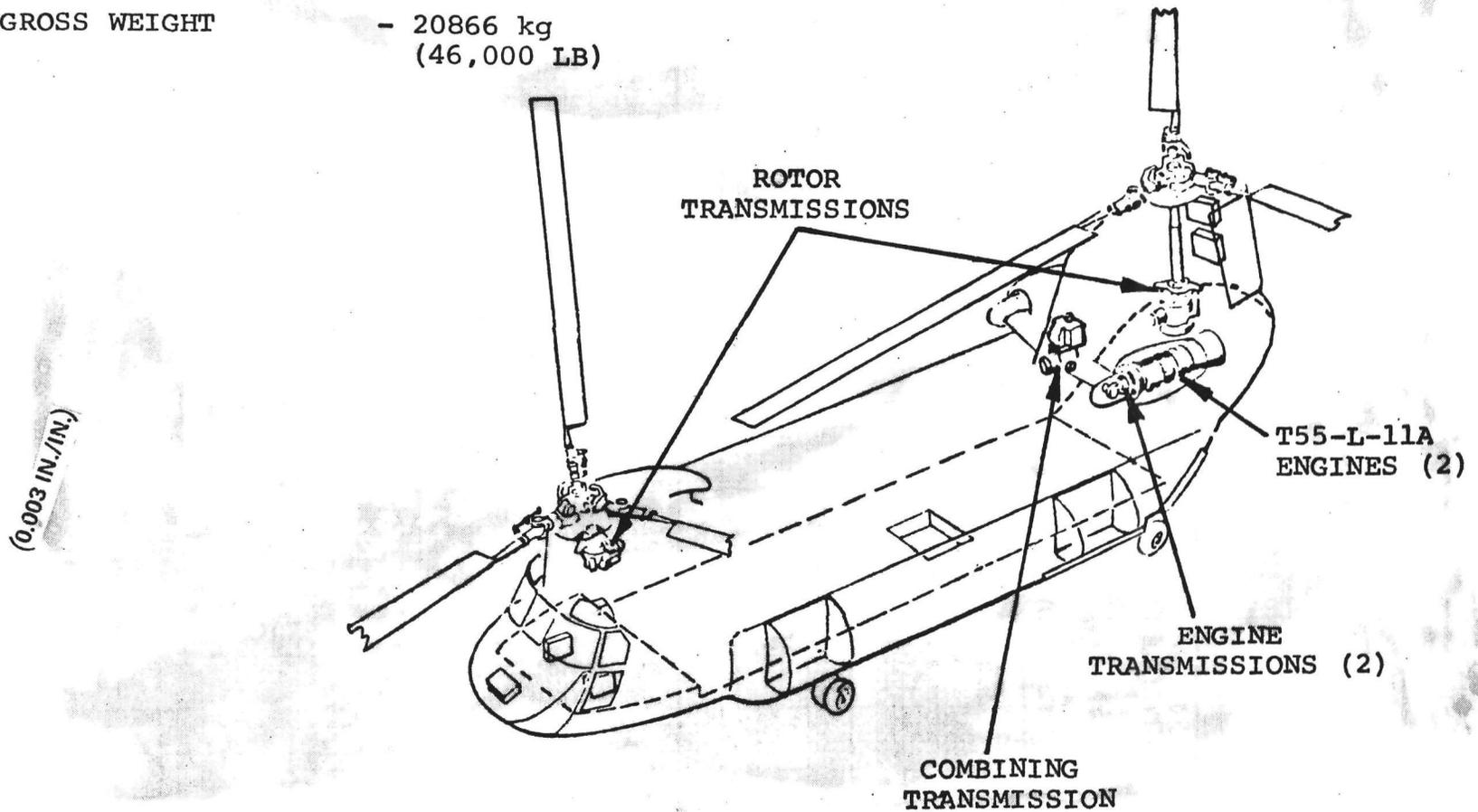


Figure 27. Boeing Vertol CH-47 helicopter

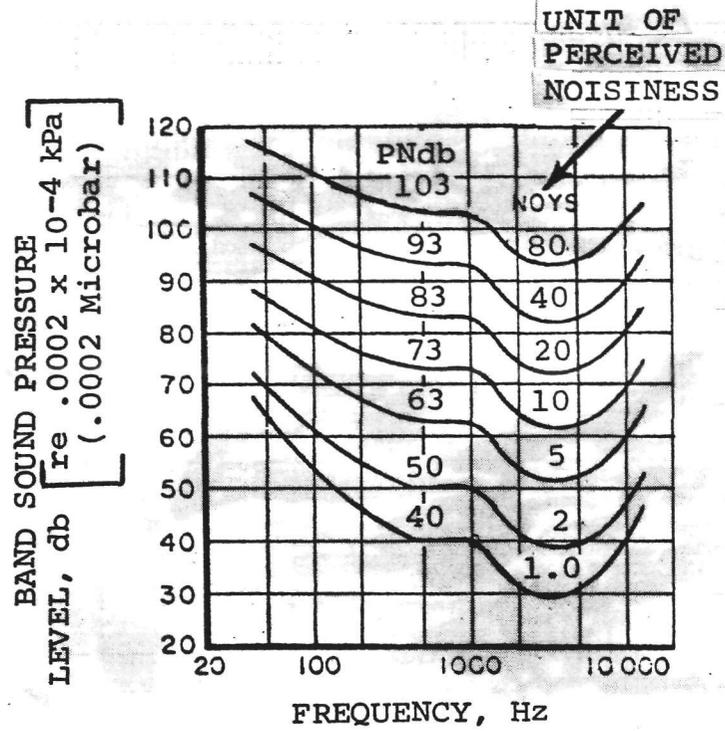


Figure 28. Perceived noisiness of bands of sound

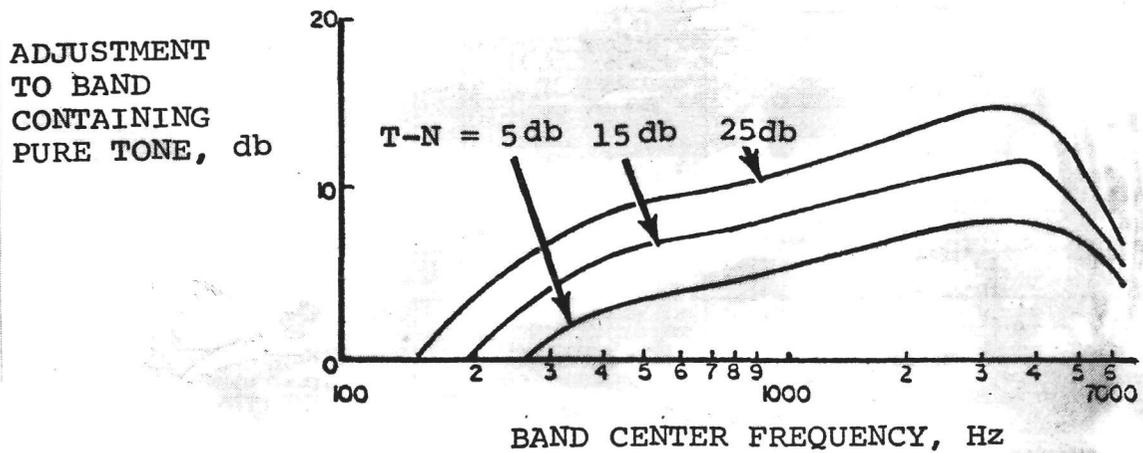


Figure 29. Tone corrections - adjustment to be added to broadband noise level (N) when pure tone (T) is present

Transmission noise and the inherent structural vibrations which generate this noise have been of concern to helicopter designers for many years. Until recently, analytical methods have not been available to predict and reduce transmission vibration and noise problems in advance. The conventional means of controlling transmission noise has generally been to add acoustical enclosures after the hardware is built and a noise problem has become evident. Since practical enclosures are limited in noise attenuation by unavoidable sound leaks in seams and access doors, adequate attenuation is not provided for advanced helicopter drive systems of increased power. Not only do these enclosures impose considerable weight and maintainability penalties, but they do not reduce the deleterious effect of the accompanying vibrations which contribute to material fatigue and fretting at joints.

The transfer of torque between mating gears is not uniform due to tooth-profile errors and the elastic deformation of the gear teeth under load. This nonuniform transfer of torque produces a dynamic force at the gear-mesh frequency (number of teeth times rpm) and its multiples which excites the coupled torsional/lateral vibratory modes of the gear shaft. This lateral vibration (or bending) produces displacements at the bearing locations which excite the housing and cause it to vibrate, thus radiating noise (Figure 30). Furthermore, the dynamic characteristics of the housing may magnify its displacements and the resulting noise.

Boeing Vertol has developed an analysis for the reduction of transmission vibration and noise at its source. Part of this technique involves the use of the NASTRAN computer program for the finite-element modeling of the transmission housing. The analysis also includes the reduction of dynamic excitation, the reduction of dynamic response, and the use of auxiliary devices for vibration absorption.

This analysis has successfully identified components and areas of the helicopter transmission where modifications will reduce vibration and noise. See Appendix A for a detailed description of this technique.

3.7 Incipient-Failure Detection

An Incipient-Failure-Detection (IFD) system can provide dramatically improved diagnostic capability for identifying and isolating drive-train discrepancies. IFD is a highly effective, relatively recent advancement in high-frequency-vibration analysis that overcomes the inherent shortcomings of conventional low-frequency-vibration techniques. The IFD sensors are low in cost, externally mounted, and require no field calibration or charge amplifiers. The IFD analyzer is portable and, because custom baselines are not required, simple to operate (similar to a vacuum-tube tester). In commercial operation the IFD system is recommended for scheduled inspections of grease-lubricated bearings (such as swashplate and drive-shaft support bearings) and for fault isolation/verification in transmissions and gearboxes where sound or oil-borne-debris indications may be ambiguous. During transmission overhaul, IFD can reduce costs by identifying incorrect removals prior to teardown, eliminating the need for time and materials consumed by teardown inspections of gear and bearing assemblies, and reducing infant mortality due to assembly-induced failure modes.

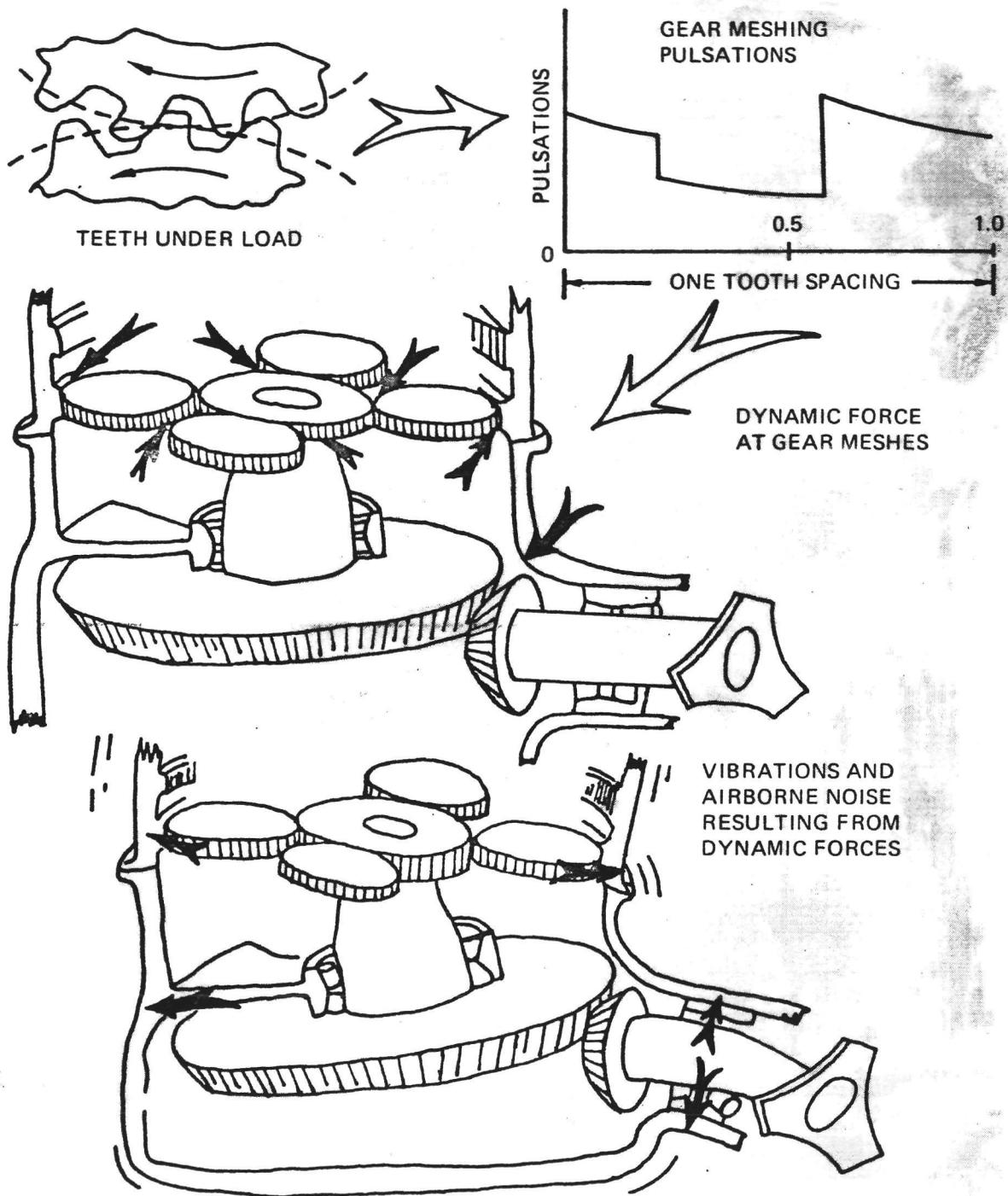


Figure 30. Sources of transmission noise

High-frequency-vibration analysis shows good potential for producing dramatic, analytically predictable signature variations from specific failure modes encountered by most dynamic-component critical-path gears and bearings (see Table 3). These dramatic and predictable signal changes from specific failure modes imply that high diagnostic accuracy may be possible.

High-frequency-vibration analysis shows excellent potential for timely diagnosis of currently undetectable and catastrophic through-the-part gear cracks.

A generic baseline (a common baseline for all components of the same part number) is practical for condition monitoring and assessment of dynamically complex components.

Although the IFD technique is a relatively recent development in the field of diagnostics, it has already achieved broad application in both aviation and nonaviation commercial and military environments. In helicopters, it has been used effectively on the CH-47, UH-1, and YUH-61A aircraft. As a consequence of this existing background, IFD systems are well along in their development and several engineering prototype units are available today. The prototype shown in Figure 31 is currently being used by NASA on the Space Shuttle Orbiter and is suitable for use on a commercial helicopter. Thus the application of IFD to a commercial helicopter would require only the identification of optimum sensor locations and indication thresholds. This can be accomplished with available IFD equipment and a limited amount of test-cell-implant testing with representative artificial defects.

Appendix B describes Boeing Vertol's experience with high-frequency-vibration analysis.

TABLE 3. SUMMARY OF EXPERIENCE WITH INCIPIENT-FAILURE DETECTION

Failure Mode	Detectability Demonstrated		
	Iron Housing	Aircraft Housing	
		In Test Stand	On Aircraft
● Tooth-Root Cracks			
Spur gears	Yes	0	0
Bevel gears	Yes	Yes	0
● Tooth-Surface Damage	Yes	Yes	0
● Bearing-Race Cracks	0	0	Yes
● Bearing-Surface Damage	Yes	Yes	Yes
● Other Bearing Modes			
Low grease level	0	0	Yes
Cage rub	0	0	Yes
Worn races	0	Yes	0
0 = Not evaluated			

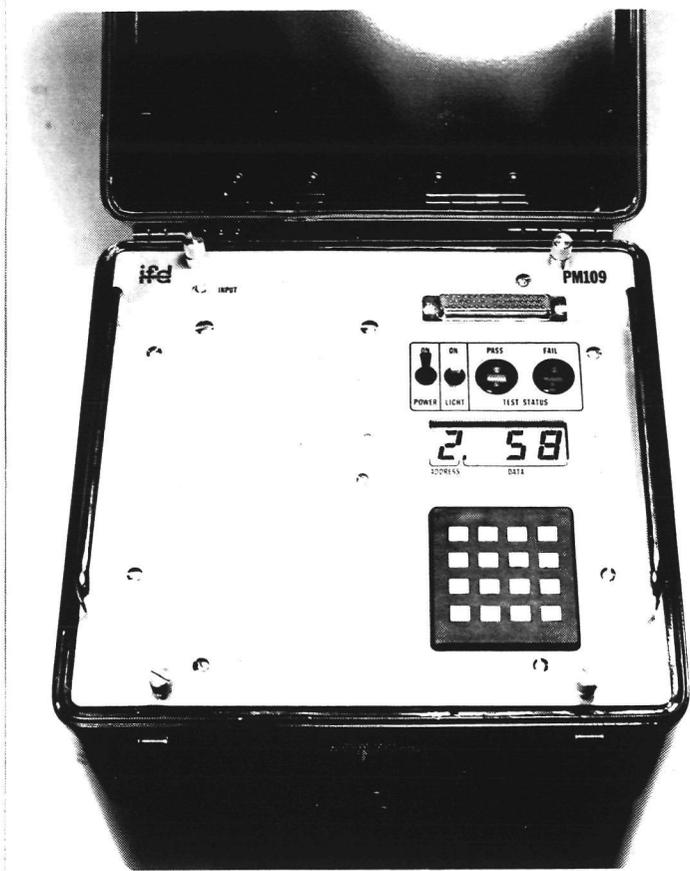


Figure 31. PM109 portable incipient-failure-detection monitor

4.0 RESEARCH AND DEMONSTRATION REQUIREMENTS

A review of drive-system literature (bibliography) indicates that improved, conventional, geared-transmission systems have the best potential for attaining the maintenance-cost-reduction goal, providing that an optimized drive-system design is implemented. Indications are that optimized designs of improved, conventional, powertrain systems have not been used in the past.

The literature review also showed that competing geared-transmission concepts, including the roller-gear planetary and the free-planetary systems when proportioned for equal function and reliability, had no significant difference in their weights.

Previous studies have concluded that totally new power-transmission systems must of necessity have more unknown failure modes than conventional systems, many of the failure modes of which have already been identified and eliminated. It has become obvious that much of the extensive knowledge obtained on basic conventional systems cannot be readily transposed to a completely new system configuration.

This contractor's past and present study efforts and drive-system research have provided knowledge in defining the course of the drive-system research and demonstration requirements to achieve the maintenance-cost-reduction goal.

The proposed approach acknowledges that some problems are related closely to certain designs, fabrication techniques, and materials currently employed and that new advances are required to further improve reliability. By careful examination of past experience, certain drive-system components have been identified as candidates for improved technology.

The approach includes advanced design analysis, integrated-component design techniques featuring dualized functioning components, advanced materials, new-concept housing design, balanced-load planetary system, advanced gear-tooth form, advanced bevel input-pinion support bearings, unique ring-gear/rotor-support bearing system, magnetic shaft oil seals, and improved lube-delivery system.

Transmission Housings

- Increased stiffness-to-weight ratio improves gear and bearing load capacity and life.
- Advanced-composite materials permit structural optimization by selective stiffening, leading to noise and vibration reduction without incurring a weight penalty.
- Advanced-composite materials eliminate corrosion problems and costly processes.

Gearing

- Improved load sharing and reduced sliding of noninvolute, high-contact-ratio spur-gear teeth provide reduced noise and vibration levels and increased load capacity and life for planetary systems.
- Increased contact area, reduced misalignment sensitivity and sliding of nonoctoid, high-contact-ratio bevel teeth provide reduced noise and vibration levels and increased load capacity and life.
- Advanced hot-hardness gear materials provide increased load capacity and life and increased tolerance to emergency oil-off operation.
- Advanced finite-element analysis of planetary (spur and helical) and spiral-bevel-gear rim thickness will preclude a catastrophic failure through the gear rim or web.
- Advanced powder-metal technology will provide cost-effective accessory gearing.

Bearings

- Advanced hot-hardness carburizing steel will reduce crack propagation, improve fatigue life, and provide scoring resistance at roller-end/race-rib interface of tapered-roller bearings.
- Thermal-expansion mounting design will improve reliability, safety, and emergency oil-off operation.
- Integral heat-pipe design will improve reliability, safety, and emergency oil-off operation.
- Advanced powder-metal technology will provide cost-effective accessory-gearbox bearings.

Lubrication System

- Advanced oil-mist delivery will reduce power loss and increase operating efficiency.
- Advanced oil-filtration techniques will increase gear and bearing life.
- Through-the-shaft and bearing-inner-race oil delivery will improve operating efficiency.
- Preconditioning run-in technique will increase gear and bearing load capacity, reliability, and life.
- Advanced higher-viscosity lubricants will increase film thickness and provide increased fatigue life and reliability for the gear and bearing system.

Drive-System Shafting

- Advanced-composite drive shafting will provide increased torsional rigidity with reduced weight.
- Improved misalignment shaft couplings will eliminate fretting, increase life and reliability.
- Improved shaft-support-bearing assemblies will increase service life.
- Improved overrunning-clutch designs will increase service life by eliminating component wear and fretting.

Main-Transmission System

- Design and analysis of an optimized, simplified, dualized functioning, integrated-component system will provide the basis for maintenance, cost, reliability, and weight predictions.
- Gear and shaft dynamic diametral-mode analysis will preclude resonance and catastrophic failure.
- Fabrication, rig test, and evaluation of an advanced, optimized, experimental main-transmission system will establish the status of component-readiness for drive-system integration.

Incipient-Failure Detection

- Advanced incipient-failure-detection (IFD) system will reduce overhaul costs by identifying incorrect removals prior to transmission teardown.
- Advanced IFD system will eliminate the need for time- and material-consuming teardown inspection of gear and bearing assemblies, and reduce infant mortality due to assembly-induced failure modes.

Program Plan

To accomplish the research and demonstration requirements, a three-phase program is envisioned as shown in Figure 32. The Phase I effort is a design investigation that can be accomplished in 9 months. Phase II covers component design, fabrication, and development and can be accomplished in 36 months. Phase III includes the final drive-system design, fabrication, and flight-testing covering a 42-month timespan. The complete program can be accomplished in approximately 7 years. The straight-line-estimated cost projection for each program phase, as accumulated cost in 1976 dollars, is shown in Figure 33.

A further breakdown of the proposed three-phase program is shown in Figures 34, 35, and 36. A four-task effort is identified for Phase I, a three-task effort for Phase II, and a five-task effort for Phase III.

YEAR	1				2				3				4				5				6				7				8	
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2
	DRIVE SYSTEM DESIGN INVESTIGATION																													
	PHASE I																													
					DRIVE SYSTEM COMPONENT DESIGN, FABRICATION DEVELOPMENT AND EVALUATION																									
					PHASE II																									
													DRIVE SYSTEM DESIGN, FABRICATION, BENCH, GTV AND FLIGHT TESTING																	
																	PHASE III													

Figure 32. Schedule for drive-system research and demonstration requirements program

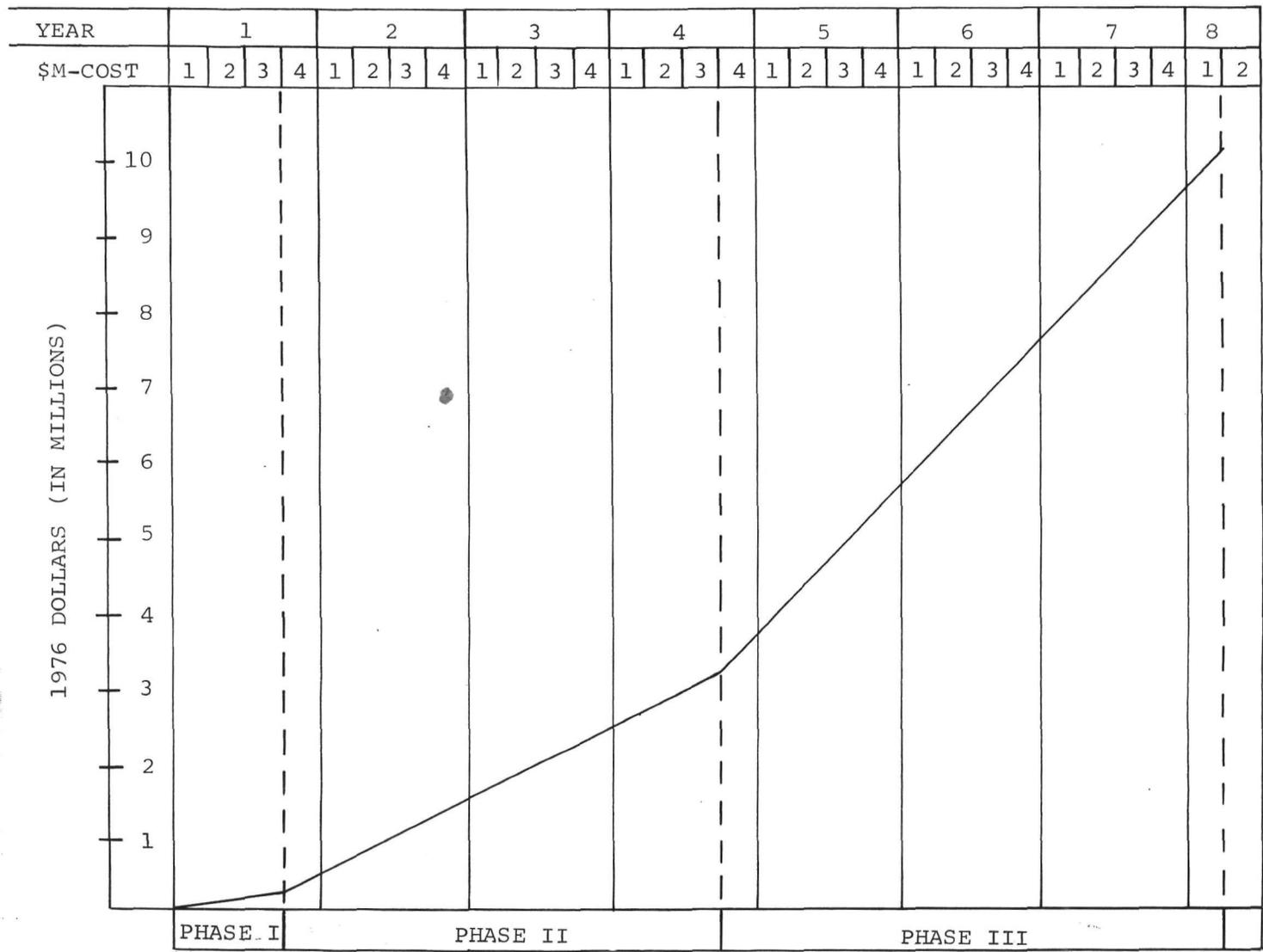


Figure 33. Estimated cost of drive-system research and demonstration requirements program

PHASE I - DRIVE SYSTEM DESIGN INVESTIGATION

TASK 1 - DEFINE BASELINE HELICOPTER DRIVE SYSTEM LOADS CRITERIA AND COMPONENT TECHNOLOGY

TASK 2 - DEFINE ADVANCED HELICOPTER DRIVE SYSTEM COMPONENT TECHNOLOGY

- TRANSMISSION HOUSINGS
- GEARING, BEARINGS AND OVERRUNNING CLUTCH
- SHAFTING, COUPLINGS AND SEALS
- LUBRICATION SYSTEM
- INCIPIENT FAILURE DETECTION SYSTEM

TASK 3 - DEVELOP ADVANCED HELICOPTER DRIVE SYSTEM CONCEPT DESIGN

- ROTOR HUB/BLADE SYSTEM INTERFACE
- TURBINE ENGINE INTERFACE
- AIRFRAME INTERFACE

TASK 4 - DEFINE ADVANCED HELICOPTER DRIVE SYSTEM COMPONENT TECHNOLOGY RESEARCH AND DEMONSTRATION REQUIREMENTS

- DESIGN TRADE-OFF INVESTIGATION
- COMPONENT SUMMARY MATRIX
- DEVELOPMENT AND DEMONSTRATION PROGRAM
- PROGRAM SCHEDULE, MANHOURS, MATERIALS, AND COSTS

Figure 34. Phase I of research and demonstration requirements for drive system

PHASE II - DRIVE SYSTEM COMPONENT DESIGN, FABRICATION, DEVELOPMENT
AND EVALUATION

TASK 5 - PREPARE PRELIMINARY ADVANCED HELICOPTER DRIVE SYSTEM DESIGN

- PREPARE INITIAL SUBSYSTEM COMPONENT DESIGNS
- PREPARE FINITE ELEMENT MATHEMATICAL MODEL FOR
 - TRANSMISSION HOUSINGS
 - DYNAMIC COMPONENTS
- CONDUCT DESIGN OPTIMIZATION ANALYSIS
- UPDATE SUBSYSTEM COMPONENT DESIGNS

TASK 6 - FABRICATE AND TEST SUBSYSTEM COMPONENT ASSEMBLIES

- PREPARE TEST PLANS FOR SUBSYSTEM COMPONENT TESTING
- DESIGN AND FABRICATE TEST RIG HARDWARE
- DESIGN, FABRICATE AND TEST SELECTED COMPONENTS
- DESIGN, FABRICATE AND TEST INTEGRATED SUBASSEMBLIES
- ANALYZE TEST DATA TO DEFINE REDESIGN AND/OR RETEST IF REQUIRED

TASK 7 - DETERMINE EACH SUBSYSTEM COMPONENTS READINESS FOR
INCORPORATION IN ADVANCED DRIVE SYSTEM

- DEFINE DEVELOPMENT AND DEMONSTRATION PROGRAM
- DEVELOP PROGRAM SCHEDULE, MANHOUR, MATERIEL AND COST ESTIMATES

PHASE III - DRIVE SYSTEM DESIGN, FABRICATION, CLOSED-LOOP (BENCH),
GTV (TIE DOWN) AND FLIGHT TESTING

TASK 8 - PREPARE FINAL ADVANCED HELICOPTER DRIVE SYSTEM DESIGN

- SELECT OPTIMIZED SUBSYSTEM COMPONENTS AND ASSEMBLIES
- INCORPORATE OPTIMIZED SUBSYSTEM FEATURES

TASK 9 - FABRICATE ADVANCED DRIVE SYSTEM COMPONENTS AND ASSEMBLIES

- PREPARE TEST PLANS FOR MAJOR TRANSMISSION ASSEMBLIES
- FABRICATE TEST ASSEMBLIES
- DESIGN AND FABRICATE TEST RIG HARDWARE
- DESIGN AND FABRICATE AIRFRAME MODIFICATIONS AND HARDWARE

TASK 10 - CLOSED-LOOP (BENCH) TRANSMISSION TESTING

- CONDUCT TESTING OF TRANSMISSION ASSEMBLIES
- ANALYZE TEST DATA RESULTS
- DETERMINE READINESS FOR GTV (TIE DOWN) TESTING

TASK 11 - GTV (TIE DOWN) DRIVE SYSTEM TESTING

- CONDUCT TESTING OF ADVANCED DRIVE SYSTEM
- ANALYZE TEST DATA RESULTS
- DETERMINE READINESS FOR FLIGHT TESTING

TASK 12 - FLIGHT TESTING DRIVE SYSTEM

- CONDUCT TESTING OF ADVANCED DRIVE SYSTEM
- ANALYZE TEST DATA RESULTS
- DETERMINE READINESS FOR PROTOTYPE AIRCRAFT INCORPORATION

Figure 36. Phase III of research and demonstration requirements for drive system

5.0 IMPACT OF INTERACTIONS

Table 4 has been prepared to identify and briefly consider the interactions of advanced-drive-system design features with other significant technological areas. The expected effect on the area, limitations inherent to the design feature in question, and suggested resolution of problems are defined. Problem resolution includes direction for trade studies and further analyses.

Interactions between a major goal such as reduction in direct operating costs and the various features of the advanced drive system could be defined more precisely by an in-depth study beyond the scope of this effort. Such a study would be concerned with the relationships between weight, size, and reliability, developmental testing and reliability, modularization of components for ease of repair, diagnostic and prognostic systems leading to decreased overhaul costs, as well as other important interactive features which would be defined. Studies such as this are recommended to provide guidelines for the establishment of a civil-helicopter technical base.

TABLE 4. TECHNOLOGICAL INTERACTIONS

	Interaction Considerations	Resulting Limitations	Suggested Resolution
Fuselage Tuning for Vibration	Space requirement for tuned rotor system impacts transmission envelope.	Accessibility for maintenance can suffer.	Reduce envelope by design and material selection for housing and transmission mounts.
Control of Interior Noise	Airborne noise reduced by analysis and appropriate stiffening of housing. Structure-borne noise reduced by low-impedance gearbox mounts and by reduction in transmissibility of connecting shafts.	Multiple frequencies generated by transmission do not permit detuning completely. Composite airframe will assist in reducing transmissibility.	Improve sound-barrier treatment of transmission compartment. Transmission-mount structure of composites; also develop composite, lightweight drive shafting.
Production	High-cost materials reduce weight and size of transmission.	Maximum weight/size reduction increases costs.	Establish cost/weight criterion.
Maintenance	Highly integrated subsystems reduce routine on-board maintenance requirements.	Removal and repair of individual components (like oil cooler) more difficult as they are more closely integrated.	Component reliability must be established early in development cycle.
Energy Use	Efficiency of gears can be improved and windage can be reduced.	Lube oils used and gear rpm limit extent of loss reduction.	Effects of materials and lubricants on efficiency should be studied.
Blade and Control-System Loads	Loads are reacted by rotor shaft and transmission housing to airframe.	Reduction in transmission envelope increases magnitude of local loads to airframe.	Airframe design for distribution of increased loads.

TABLE 4 – Continued

	Interaction Considerations	Resulting Limitations	Suggested Resolution
Drive-System Noise	Tuning of housings by composite construction can reduce noise.	Required materials add weight and cost.	Optimize distribution of noise-reducing material between housing and transmission enclosure.
Safety	Failsafety and fracture toughness in design and construction of rotor-load paths are required.	Higher modulus/higher strength materials tend to brittleness.	Mix moduli and strengths to achieve required properties at some cost to structural efficiency.
Transmission Efficiency and Weight	Efficiency must be maximized by reducing number of meshing components and by operation in hydrodynamic regime.	Arrangement of engines, rotor, and airframe must consider simplified drive train.	Consideration of drive-train losses in aircraft design selection.
Empty Weight	Required MTBR, safety features, accessory drives, rotor and control loads impact transmission weight.	—	Factor increased requirements into transmission weight when estimating from historical trend curves.
Drive-System Loads and Maintenance	Rotor torque increases if rpm decreases for rotor noise. Maintenance decreases with fewer components.	—	—
Reliability	Increased reliability (higher MTBR) very effective in reducing life-cycle costs of aircraft.	Extremely high MTBR requirements increase weight and cost.	Set realistic MTBR goals consistent with expected usage and maintenance concepts.

6.0 CONCLUSIONS

The use of the proposed advanced-drive-system technological features will have a significant impact on the reduction of direct maintenance costs with accompanying reduction in civil-helicopter operating costs. A high probability of success is forecast for achieving an average transmission life of 6,000 hours (on-condition removal), thereby extending the service life of the major drive-system components.

A technological research and demonstration program requiring an investment of 10 million 1976 dollars, judiciously applied to attain the objective of using this technology by 1985, has been identified.

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APPENDIX A

ANALYSIS OF VIBRATION AND NOISE

A three-pronged analysis for the reduction of vibration and noise at its source has been developed which includes the reduction of dynamic excitation, the reduction of dynamic response, and the use of auxiliary devices for vibration absorption. Controlling the dynamic response of the transmission is a desirable approach to noise reduction since avoidance of resonance reduces shaft deflections at the bearings; this in turn increases the life of dynamic components and transmission reliability. The finite-element modeling of the transmission housing using NASTRAN is an integral part of this analytical technique.

Reduction of the dynamic excitation of the housing is accomplished by minimizing the dynamic forces at the shaft-support bearings. This is a twofold task. First, the excitation due to the dynamic tooth forces is calculated from the gear geometry and operating conditions. Second, the damped-force response of the shafts responding to the tooth-mesh excitation loads is calculated from a finite-element model and the shaft is detuned using strain-energy methods to minimize the displacement at the bearings. The development of this method, accomplishment of extensive dynamic testing, and correlation of data have been documented. Finally, the dynamic forces associated with the optimum configuration of the internal components are then applied to excite the model of the housing. To study the response of the transmission housing to these forces and to minimize the noise produced, a finite-element model of the housing was developed and analyzed using NASTRAN.

The Boeing Vertol CH-47 forward-rotor-transmission housing is composed of three major sections: upper cover, ring gear, and case (Figure A-1). The upper cover provides lugs for mounting the transmission to the airframe and transmits the rotor-system loads. The case contains and supports the main bevel gears. The ring gear, which connects the upper cover and case, contains the planetary-gear system. This natural division of the housing was adhered to for ease of modeling (Figure A-1).

The geometric grid points for the model were defined from design drawings and by cross-checking on an actual housing. CQUAD2 (quadrilateral) and CTRIA2 (triangular) homogeneous plate (membrane and bending) elements were used to connect the grid points and build the NASTRAN structural model. A Boeing Vertol preprocessor program (SAIL II, Structural Analyses Input Language) for the automatic generation of grid-point coordinates and structural-element connections was used. This preprocessor allows the user to take advantage of any pattern which occurs in the data by providing straightforward techniques for describing algorithms to generate blocks of data. The extensive computer-generated plotting capability of NASTRAN was used to debug the structural model.

In order to minimize the matrix bandwidth for most efficient running of NASTRAN, the BANDIT computer program was used. Grid points are used to apply the dynamic excitations at the mesh frequencies to analytically excite the housing. Although each geometric grid point has six possible degrees of freedom (3 translational and 3 rotational), the displacements

normal to the outer surface of the housing are of most interest for noise evaluation since it is this out-of-plane motion which generates sound waves (Figure A-2). To conveniently evaluate the motion normal to the housing surface, numerous local-coordinate systems were defined and oriented such that the displacements and accelerations calculated at each grid point could be referred to a coordinate system having an axis normal to the housing surface.

Strain-energy techniques for structural optimization have evolved in recent years. For applications such as helicopters where weight is critical, it is more appropriate to evaluate the strain-density (strain energy/volume) distribution within a structure which provides guidance for vibration reduction by identifying the structural elements participating in the modes. To optimize a housing for minimum vibration and noise, the natural frequencies are calculated and compared with the gear-mesh exciting frequencies to identify each mode shape whose natural frequency is close to an exciting frequency, since a minimal weight change will yield a maximum shift in natural frequency. By locally altering the housing wall to change the mass and stiffness in these areas of high strain density, the natural frequency may be shifted away from an exciting frequency (Figure A-3). Thus, the possibility of resonance is eliminated and the vibration and radiated noise are reduced.

A complex gearbox such as a helicopter-rotor transmission typically has more than one gear mesh, hence more than one exciting frequency. This occurrence of multiple exciting frequencies, coupled with the fact that the housing possesses many natural frequencies, makes it a complex task to detune the housing so that none of the exciting frequencies coincides with a natural frequency.

The analysis has indicated that by modifying the gear/shaft/bearing-system geometry the internal components may be detuned to minimize excitation of the housing. Application of strain-density techniques to these dynamic components has identified modifications which have analytically reduced the loads exciting the housing at the bevel-mesh, LP2, and LP3 frequencies. Loads at the LP1 frequency increased. Since the effects of multiple noise sources are added logarithmically, the reduction of three out of four noise sources may not appreciably reduce the overall noise level.

Noise measurements have tended to confirm that housing responses exist and generate noise. This is evidenced, for example, by the LP2 and LP3 frequencies. Although the exciting source for these frequencies is within the ring gear, the maximum noise at these frequencies emanates from the midcase region (Figure A-4).

Some of the calculated natural frequencies of the housing and the main exciting frequencies are plotted on the spectrum shown in Figure A-5. A NASTRAN plot of the housing 46th mode, which has a natural frequency closest to the LP2 exciting frequency, is shown in Figure A-6. It is important to note that since the exciting frequencies will vary with changes in operating speed, the housing must be detuned at a specific operating speed. The use of strain density has led to preliminary identification of the areas (see shaded elements, Figure A-7) of the housing structure which will be modified to detune the housing for reduced vibration and noise.

CH-47 FORWARD TRANSMISSION

TRANSMISSION HOUSING MODEL

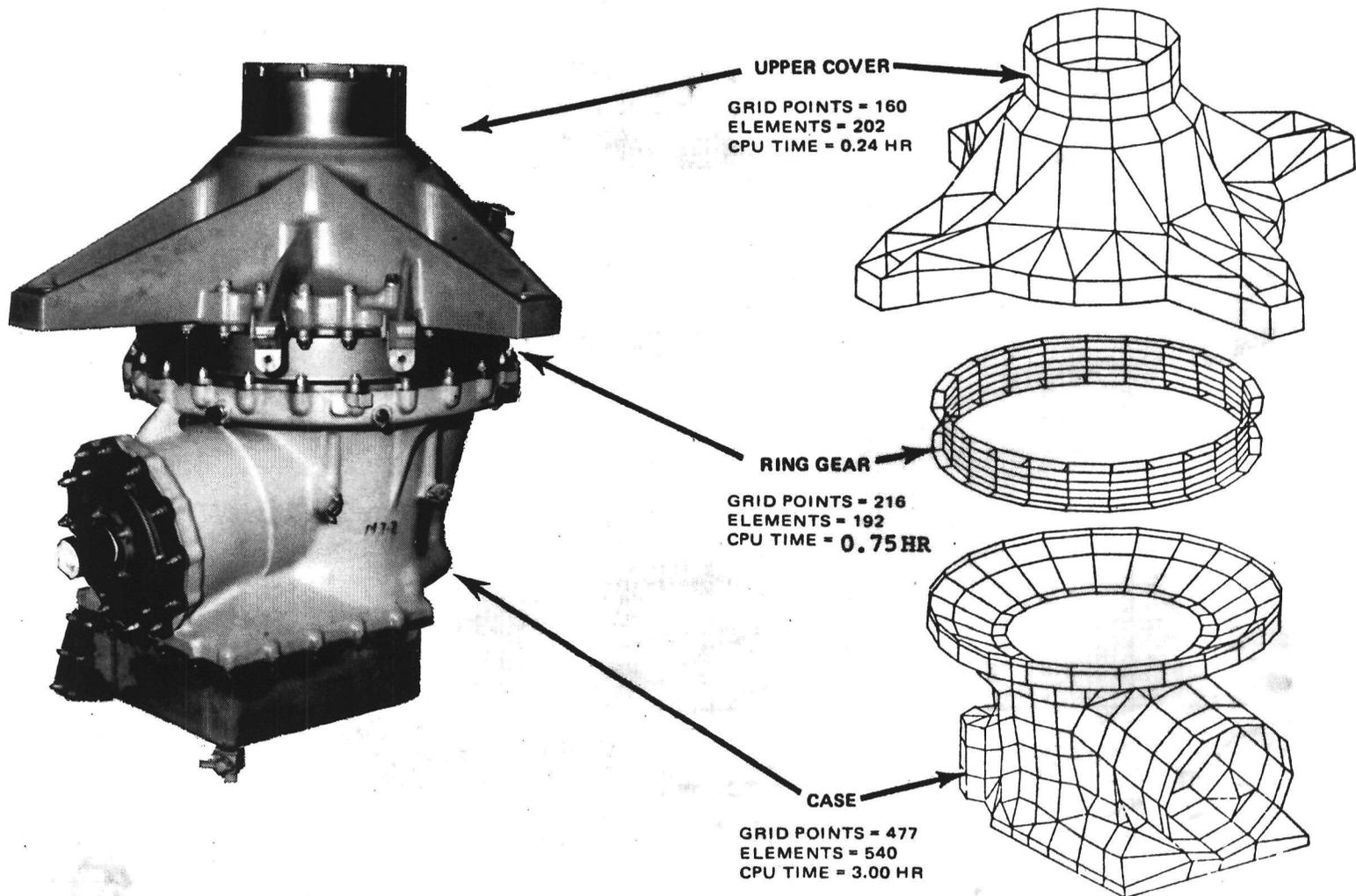


Figure A-1. Boeing Vertol CH-47 helicopter forward-rotor transmission housing and NASTRAN model

DISPLACEMENTS

T_1 = Out-Of-Plane

T_2 = In-Plane

T_3

ROTATIONS

R_1 = Fixed

R_2 = Unrestrained

R_3

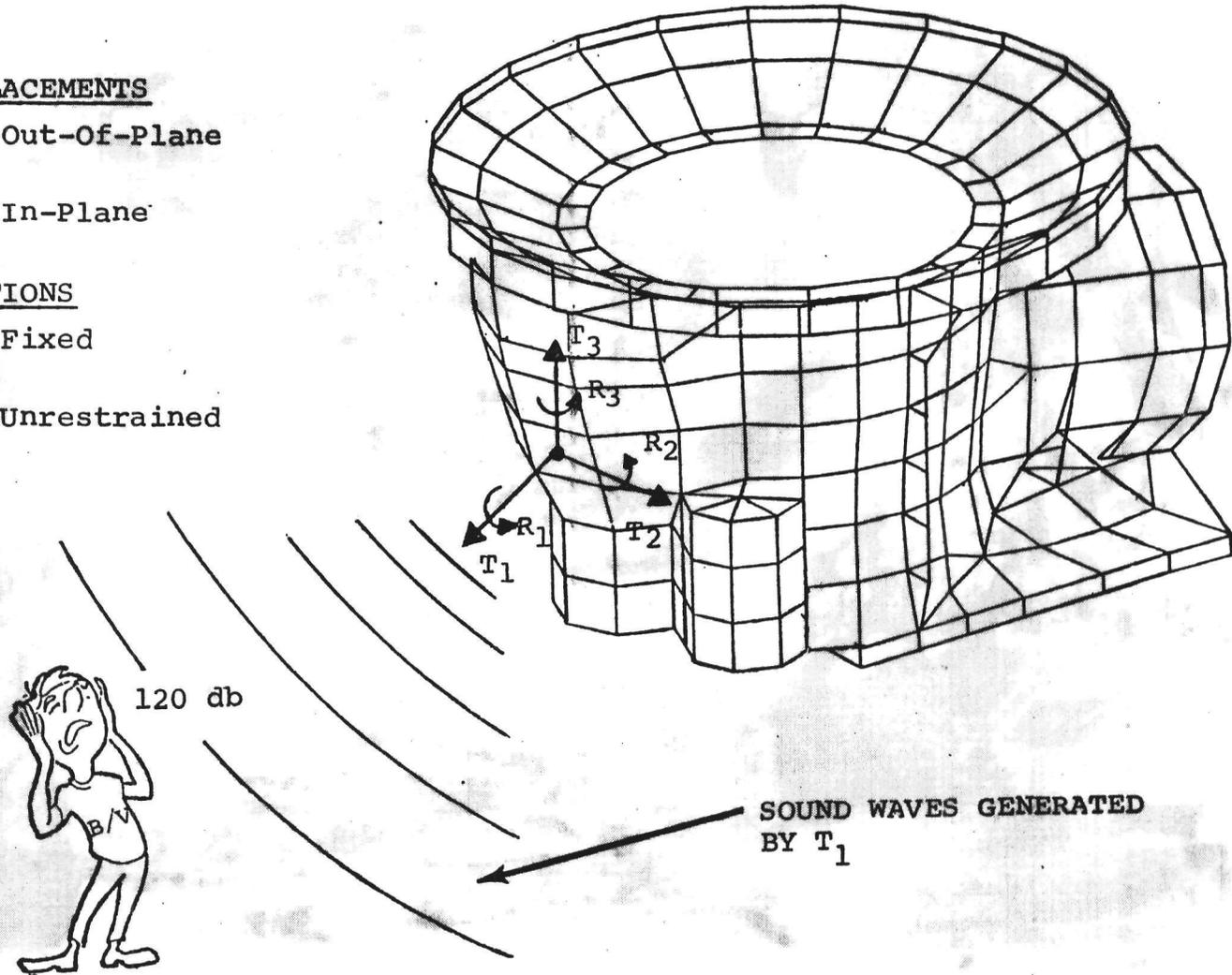


Figure A-2. Transmission noise generated by out-of-plane displacements of housing

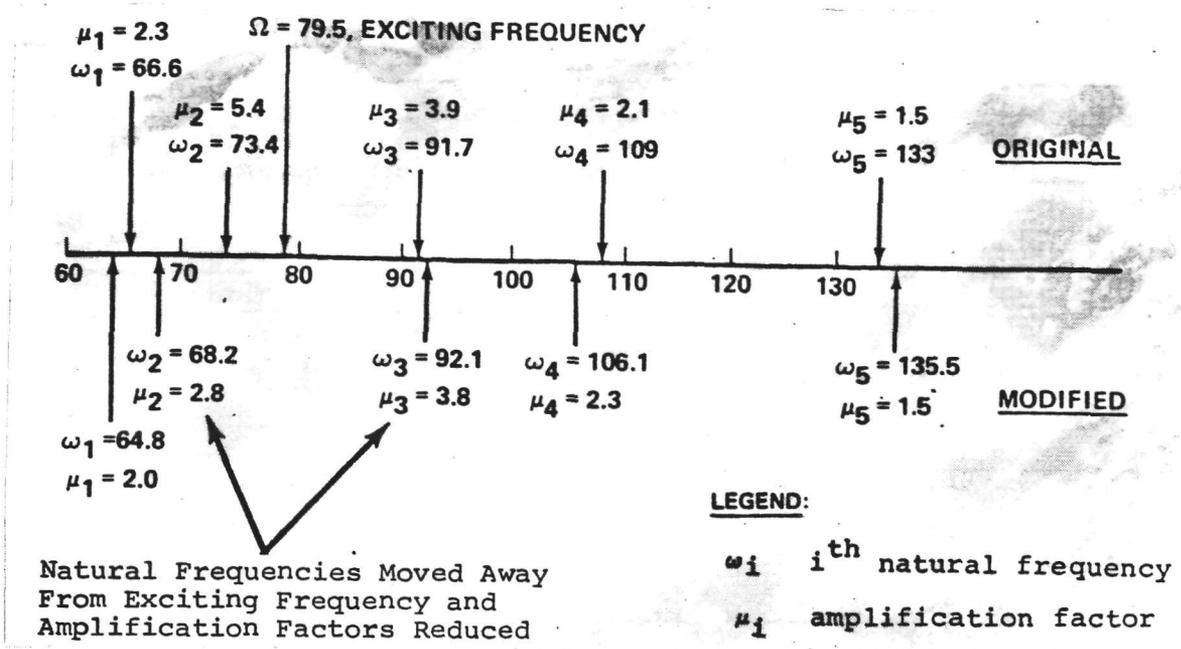


Figure A-3. Example of optimization of natural-frequency spectrum of CH-47 helicopter fuselage forward-pylon structure

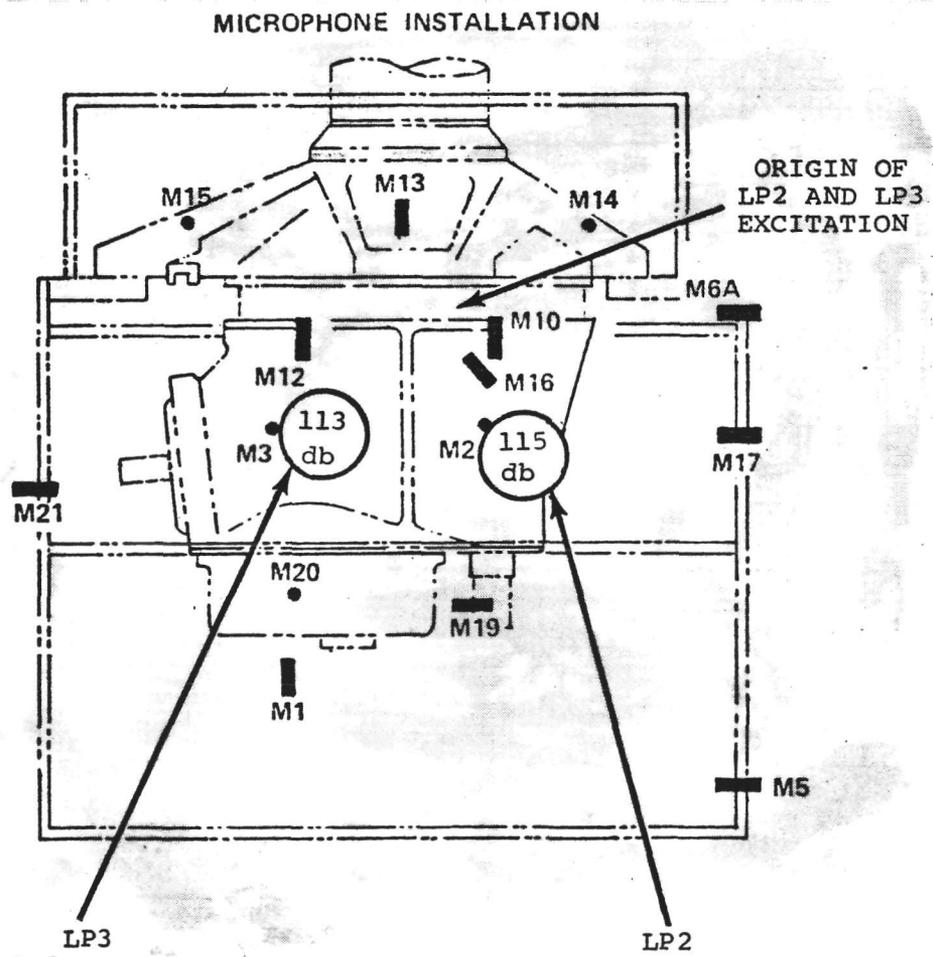


Figure A-4. Maximum measured noise levels (7,460 rpm at 80 percent torque)

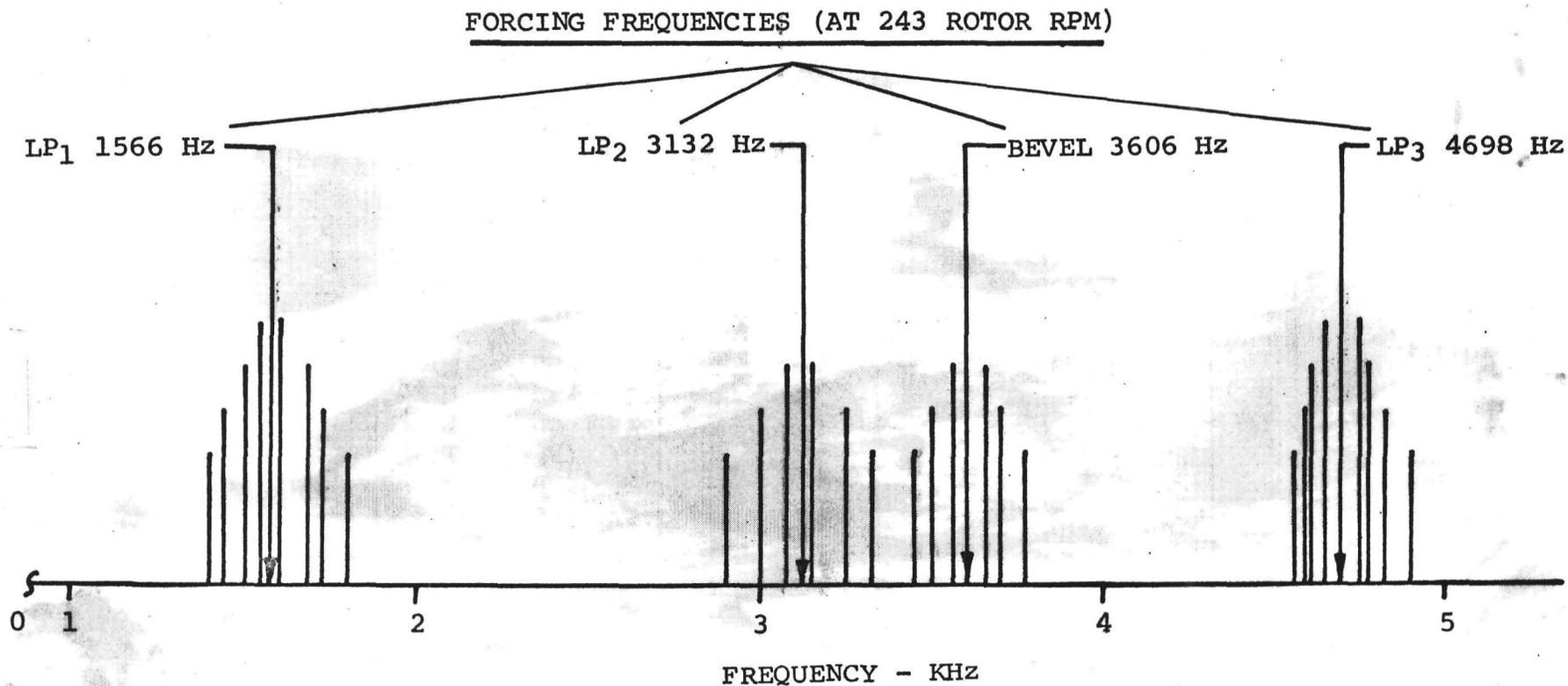


Figure A-5. Spectrum of forcing frequencies versus NASTRAN-predicted natural frequencies for CH-47C forward-transmission case

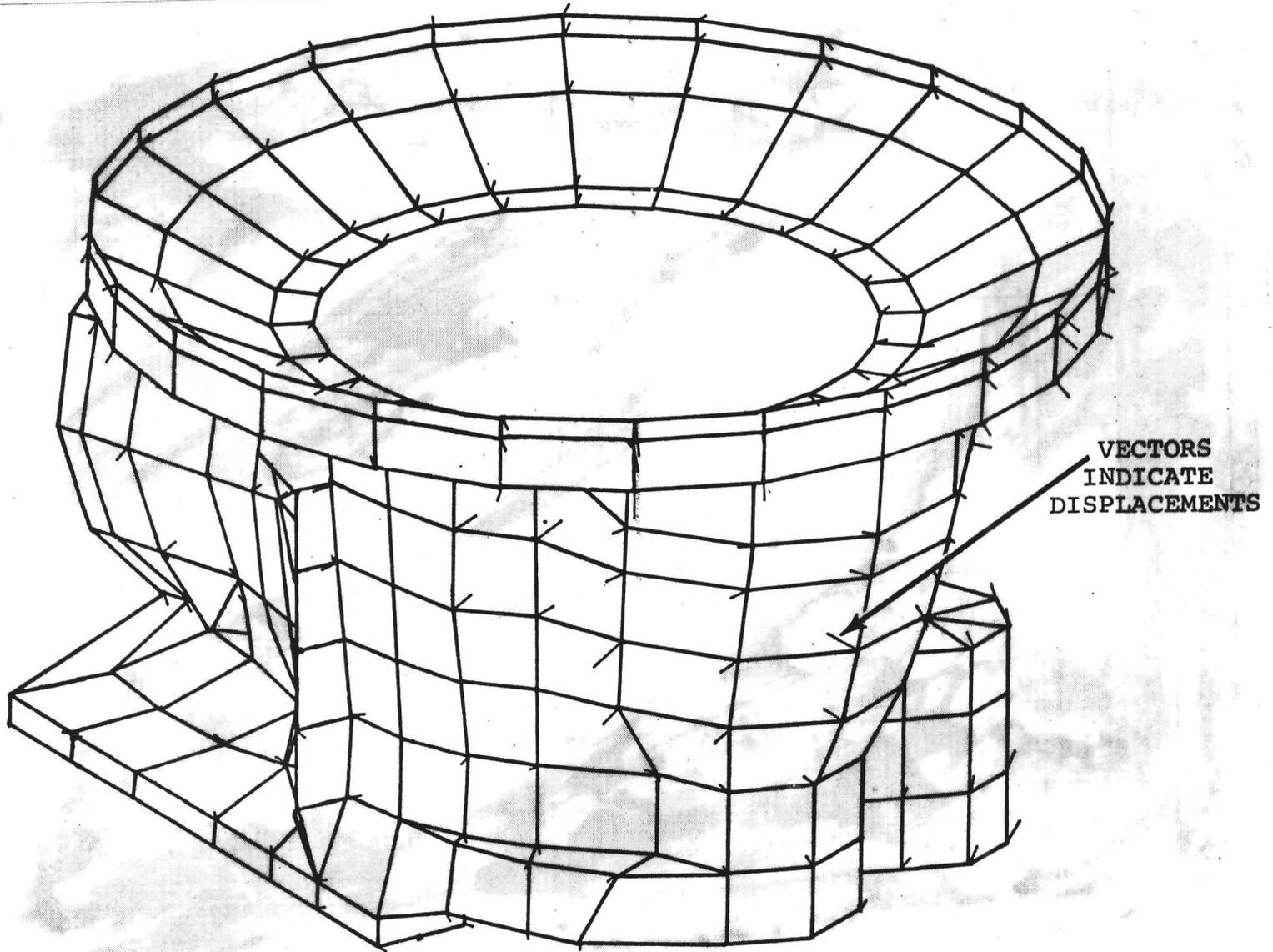
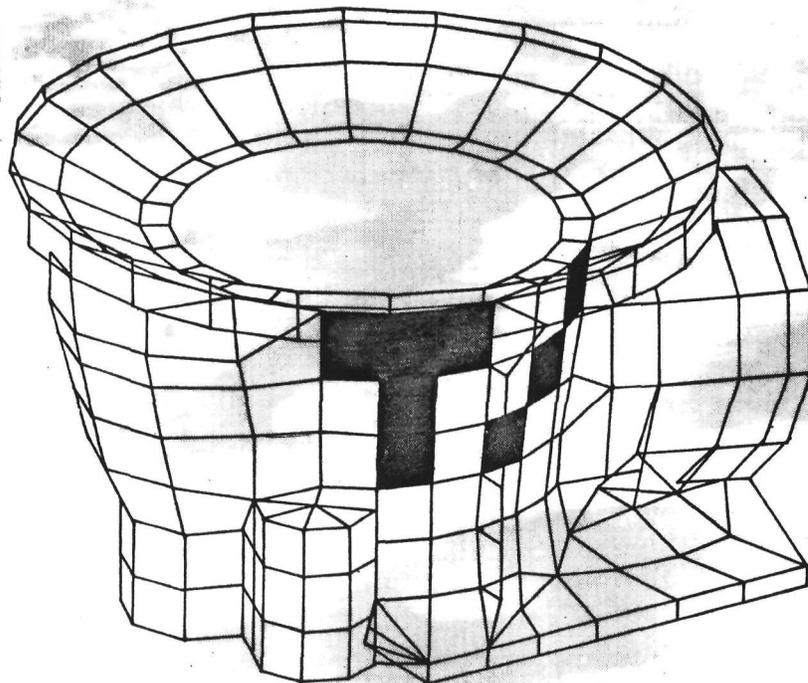


Figure A-6. NASTRAN plot of deformed housing, mode 46, frequency 3,141 Hz



LEFT SIDE VIEW

FRONT VIEW

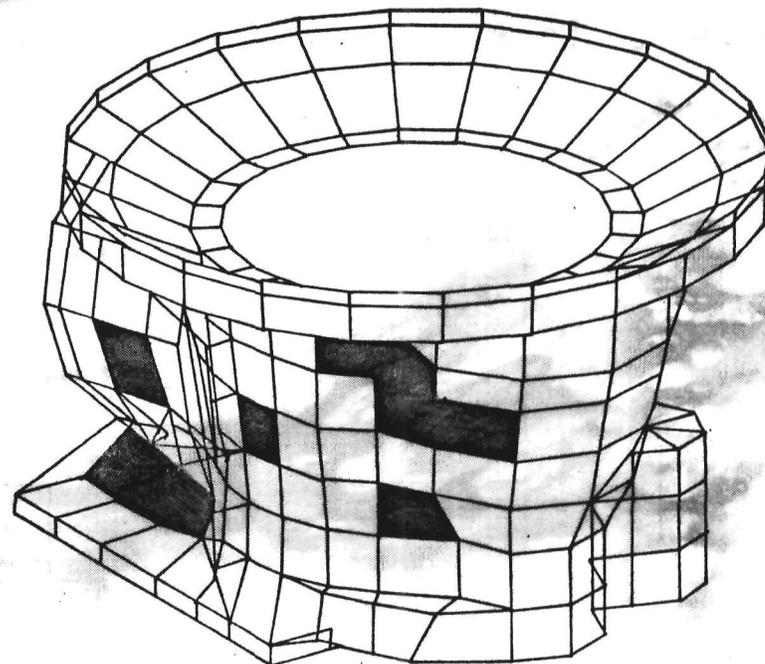


Figure A-7. CH-47 forward-transmission NASTRAN model areas of high strain density

APPENDIX B

HIGH-FREQUENCY-VIBRATION ANALYSIS

Boeing is the industry forerunner in the application of high-frequency-vibration analysis for monitoring drive-train components. To accomplish this, both baseline and discrepant-part signatures were obtained through testing on:

- Spur and spiral-bevel-gear developmental test stands
- Transmissions in test cells
- The YUH-61A ground-test vehicle.

The basic premise of high-frequency-vibration monitoring is that dynamic events related to defects in rotating machinery will cause amplitude modulation in the time domain across a broad frequency spectrum. Thus, each time a bearing's rolling element impacts a spall on the outer race, it will result in amplitude modulations at frequencies well above the machine's fundamental and lower-harmonic frequencies where a considerable amount of noise exists.

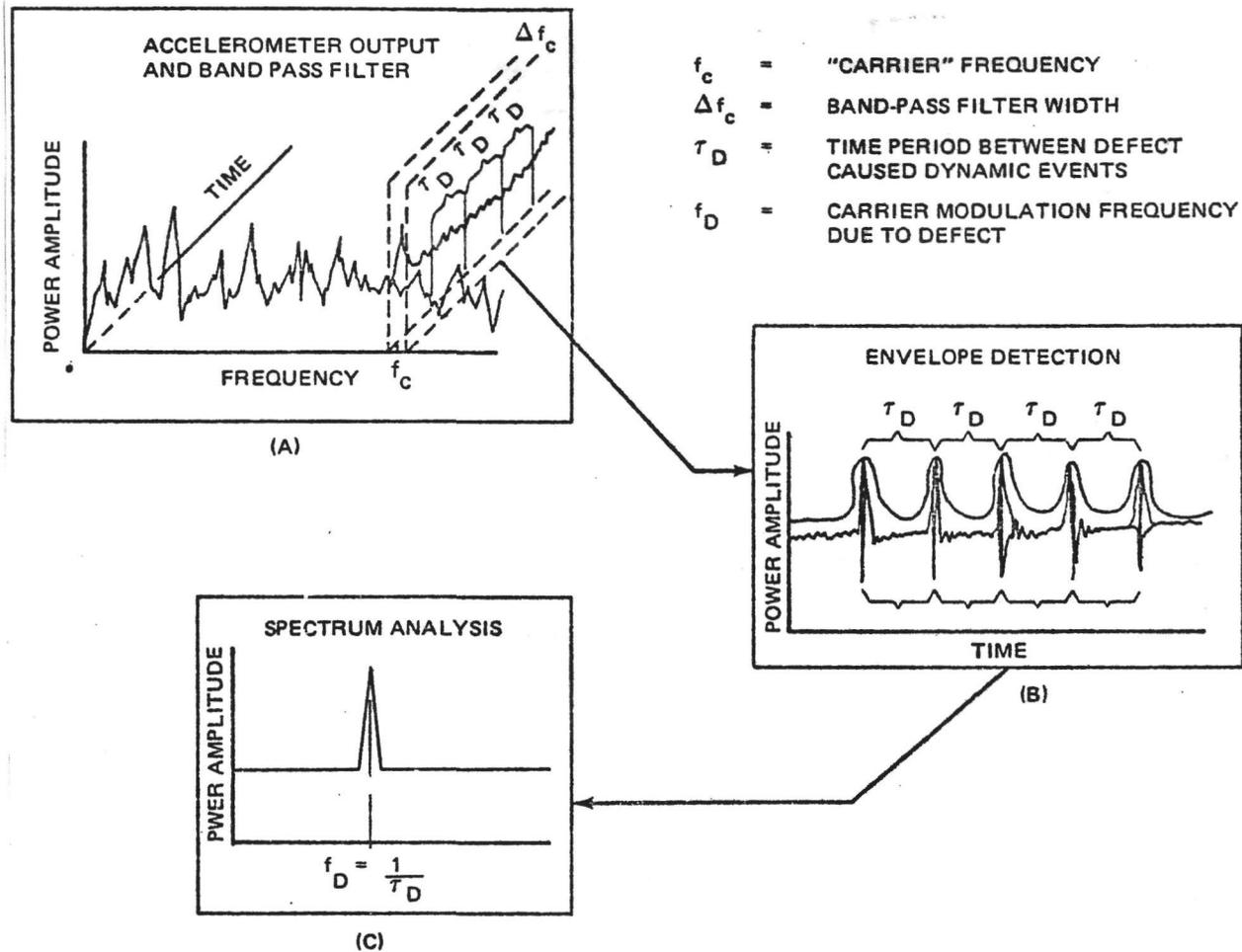
A bandpass filter can monitor amplitude variations of a narrow band of energy at a low-noise carrier frequency while screening out energy variations in the rest of the frequency spectrum (Figure B-1A). In the case of a damaged bearing, the carrier frequency will be amplitude-modulated by the impact energy each time a rolling element passes over the spall. The high carrier-frequency energy is then envelope-detected to remove high-frequency components and produce a signal with amplitude modulations at the rolling-element pass frequency over the defect on the bearing race (Figure B-1B). Therefore, spectrum analysis of the envelope-detected signal will show a strong peak at the defect frequency but a relatively flat response at all other frequencies (Figure B-1C). Figure B-2 illustrates the dramatic improvement over conventional low-frequency techniques that this high-frequency approach provides for diagnostic discrimination between a good and a bad bearing.

High-Frequency Signal-Processing Hardware

Three basic pieces of high-frequency signal-processing hardware were designed, built, and maintained to support both IR&D and government-contract-funded tests.

The first piece of hardware built was a portable 4-channel demodulator (for envelope detection) that was employed in conjunction with Army-owned, variable-bandpass filters that isolated the high-frequency carrier signals from background vibration. This unit employed breadboard prototype circuitry later incorporated in a 13-channel system and provided a limited interim data-collection capability until the larger system became available.

As demand for use of this equipment expanded and the need for simultaneous data acquisition at remote test sites became apparent, a second 4-channel system was built. However,



- A "Carrier" frequency is selected at a sufficiently high value (> 25 KHz) that it is not affected by normal transmission noise, but at a low enough value (< 500 KHz) that it is amplitude modulated by periodic defects.
- The band-pass filtered carrier frequency signal is amplitude demodulated (envelope detected) back into a low frequency (0-20 KHz) signal.
- The demodulated carrier is spectrum analyzed and limit exceedance monitored to detect and isolate the defect (via its characteristic frequency in the machine).

Figure B-1. High-frequency-vibration analysis

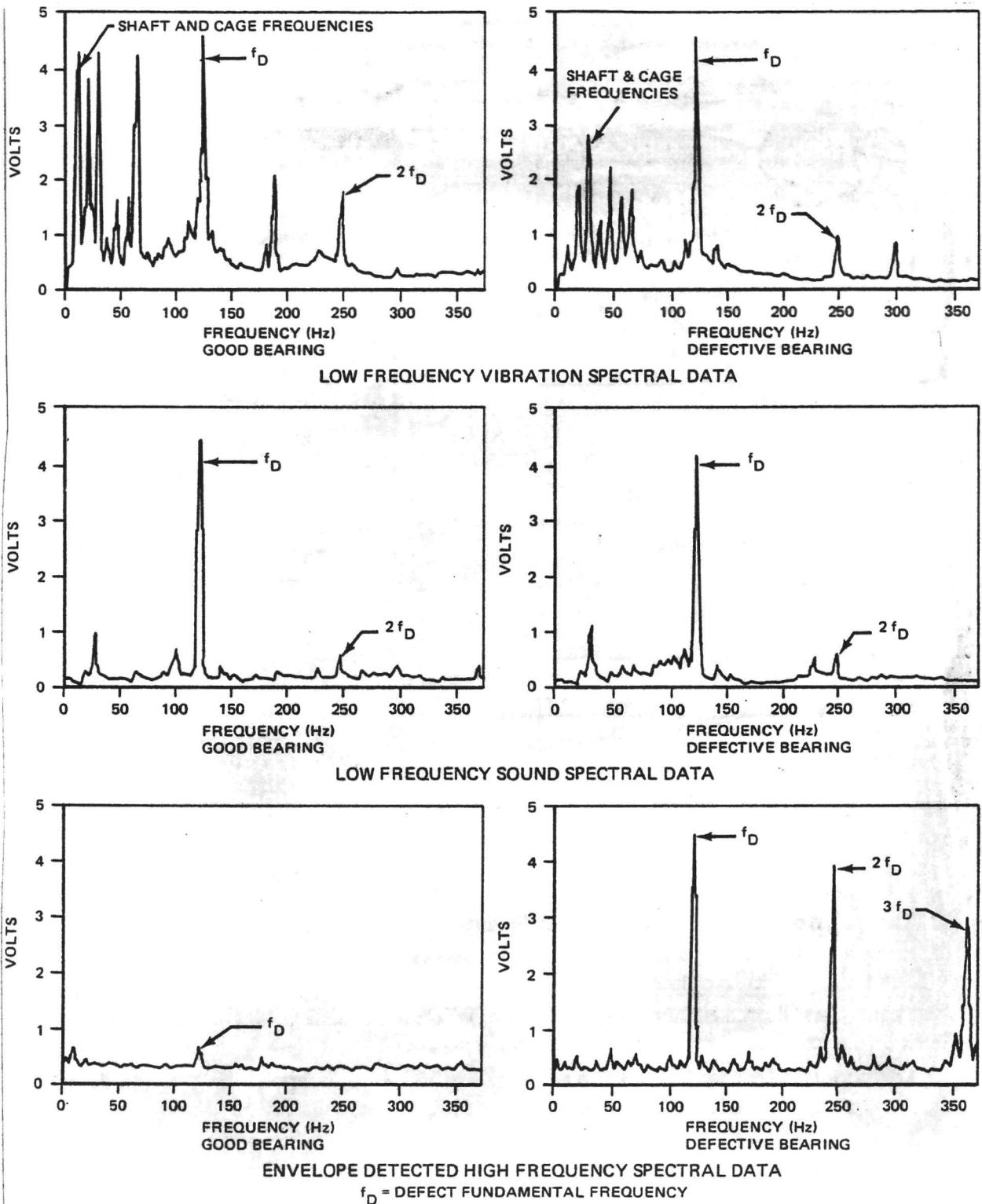


Figure B-2. Comparison of various techniques for detecting a race defect in a roller bearing

this second 4-channel system differed from the first in that four variable-bandpass filters were built in, so that it would be easily portable and totally self-contained.

The third and final piece of hardware was the 13-channel system. This hardware incorporates many additional features to facilitate high-frequency-vibration research as well as the capability to process low-frequency vibration and acoustic-emission signals. This system is highly flexible and can process up to 13 channels of simultaneous data; or individual channel modules can be removed for use as self-contained signal processors at remote test locations (see Figure B-3).

In addition to the signal processors, a special low-cost piezoelectric accelerometer was developed for use in high-frequency-vibration research. This transducer is particularly well-suited to this work due to its high signal output which eliminates the need for a charge amplifier, its high-frequency response which permits use of carrier frequencies as high as 0.5 megahertz, and its low cost (approximately \$25) (see Figure B-4).

Gear Developmental-Test-Stand Results

Two closed-loop gear-development test stands were employed to evaluate the detectability of gear discrepancies by high-frequency-vibration monitoring. One of these test stands is configured for spur-gear testing and the other is used for spiral-bevel gears. The discrepancies and failure modes evaluated were corrosion, tooth spalling, and through-the-part gear-web cracks originating at a tooth root.

Gear-tooth spalling was clearly detectable on both high- and standard-contact-ratio spur gears as well as on spiral-bevel gears. The defect signatures manifested one-per-rev and harmonic-frequency peaks with an amplitude of more than 20 db above the baseline norms. The relative amplitudes of one-per-rev and harmonic peaks were found to be related (in an analytically predictable manner) to the number of spalled teeth and their relative positions around the gear.

Corrosion on one of the spiral-bevel-gear test specimens was also detectable. The corrosion case generated a signature in the same manner as spalling, but with lower peak amplitudes that decreased to normal baseline levels as the gear cleaned itself up with increasing running time.

The through-the-part crack-failure mode was also detectable on both spur and spiral-bevel gears with one-per-rev and harmonic amplitudes as high as 10 to 20 db above baseline levels (see Figure B-5). A detailed description of this work is found in reference 1.

Transmission-Test-Cell Results

Data was accumulated from four transmission-test-cell programs:

- The HLH aft-rotor transmission
- CH-47 engine and combining transmission

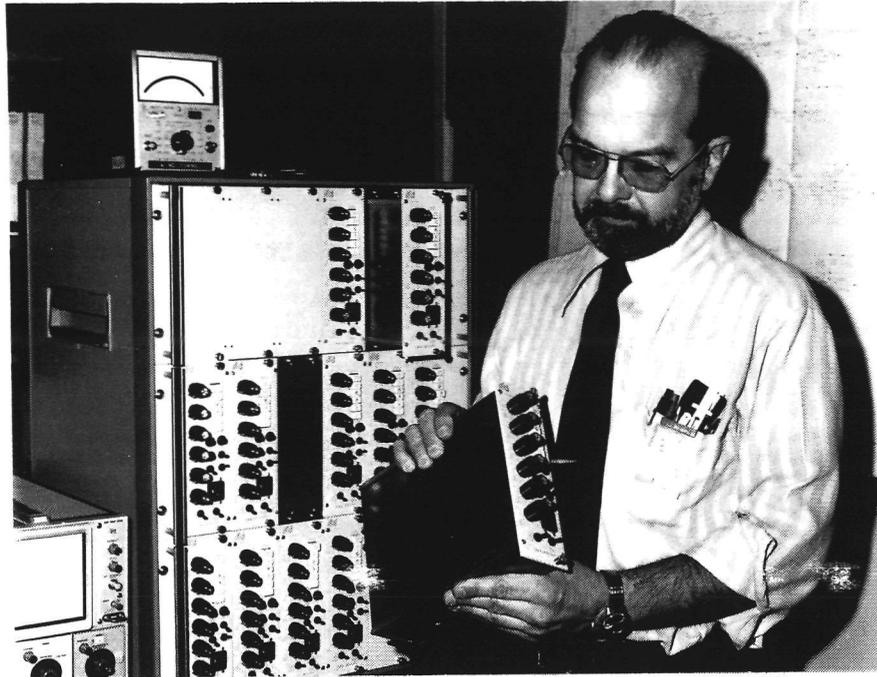


Figure B-3. Modular 13-channel high-frequency-vibration system



Figure B-4. High-frequency-vibration sensor (shown prior to potting)

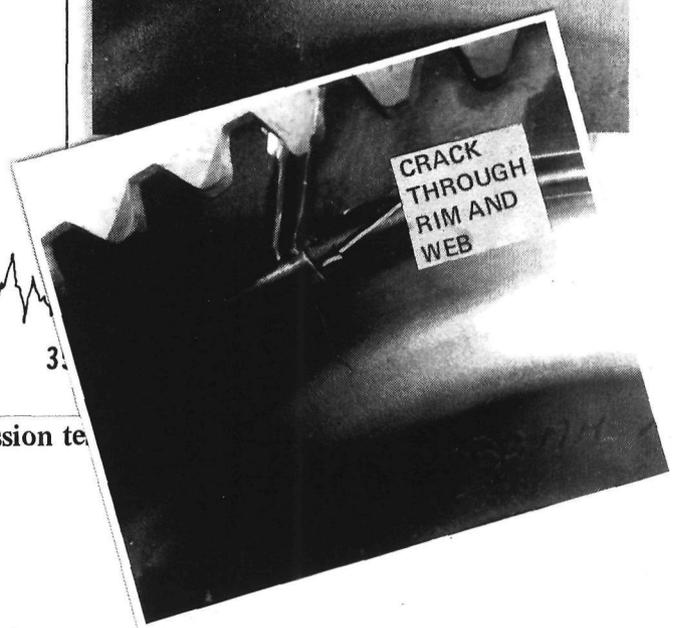
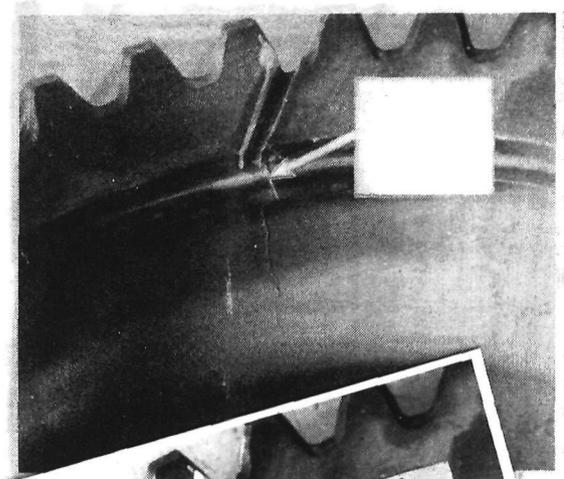
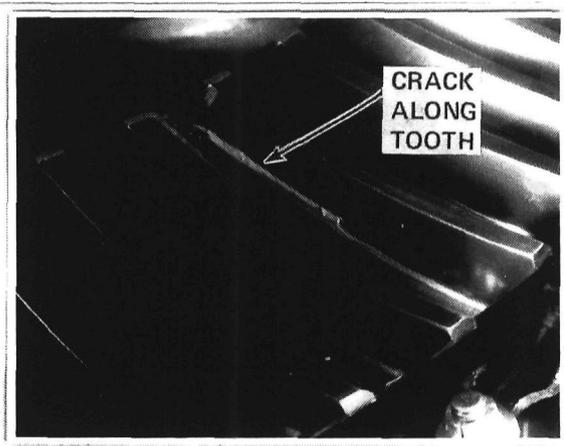
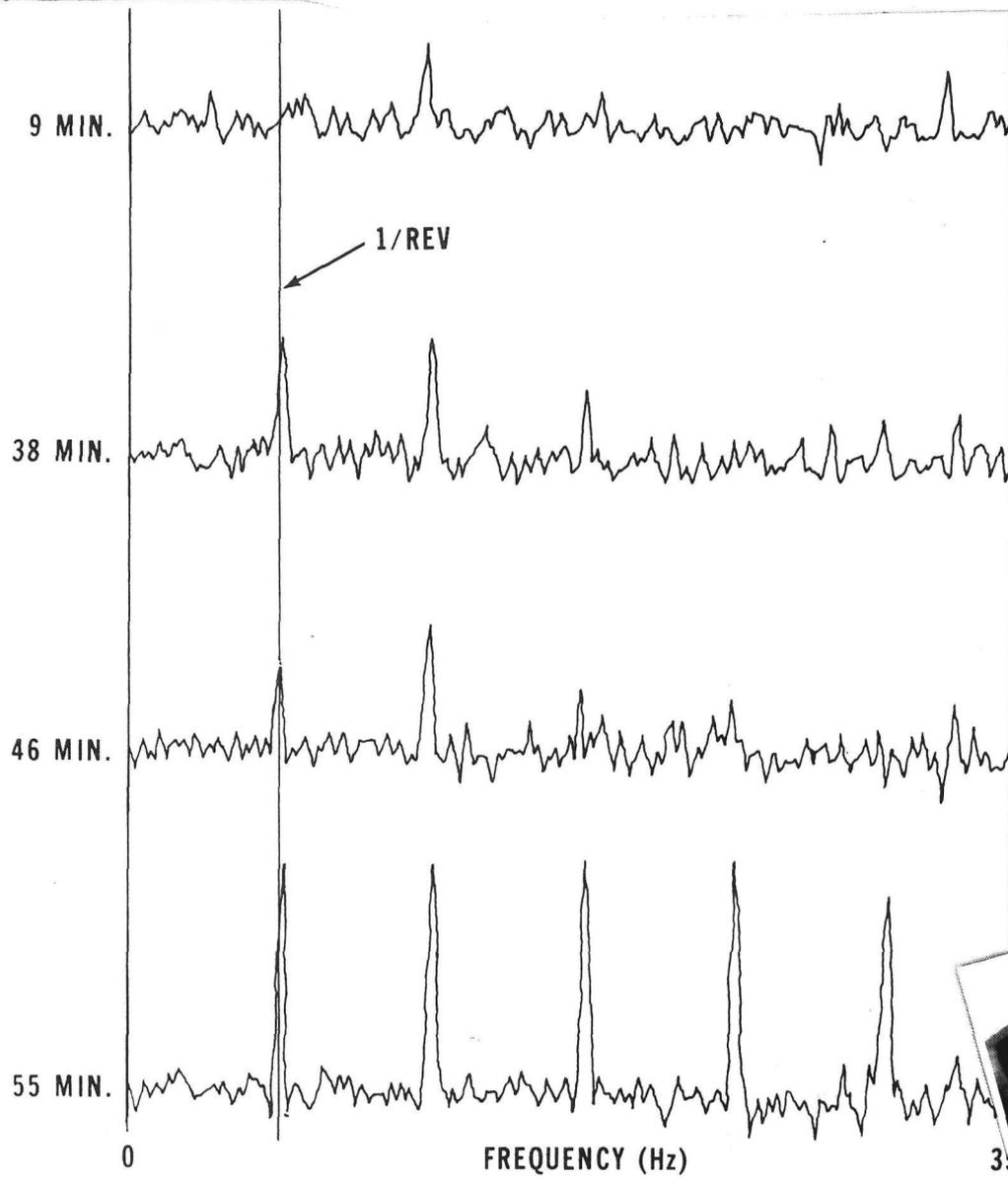


Figure B-5. Spiral-bevel-gear crack-progression test.

- CH-47 forward and aft-rotor transmissions
- YUH-61A UTTAS engine, main, intermediate, and tail-rotor transmissions.

During the test of an HLH aft-rotor transmission, a crack originated at the root of a tooth on the input pinion and propagated through the gear web to the shaft, causing a catastrophic failure. Although high-frequency data was not being realtime monitored, it was being recorded on tape during the last 2 hours of testing.

Subsequent analysis of data from the input-pinion sensor showed that dramatic peaks, greater than 20 db above baseline norms, had appeared more than 30 minutes prior to failure and persisted to the end of the test. Data from low-frequency-vibration sensors and microphones, also installed during the test, did not show analogous changes prior to the gear failure (see Figure B-6).

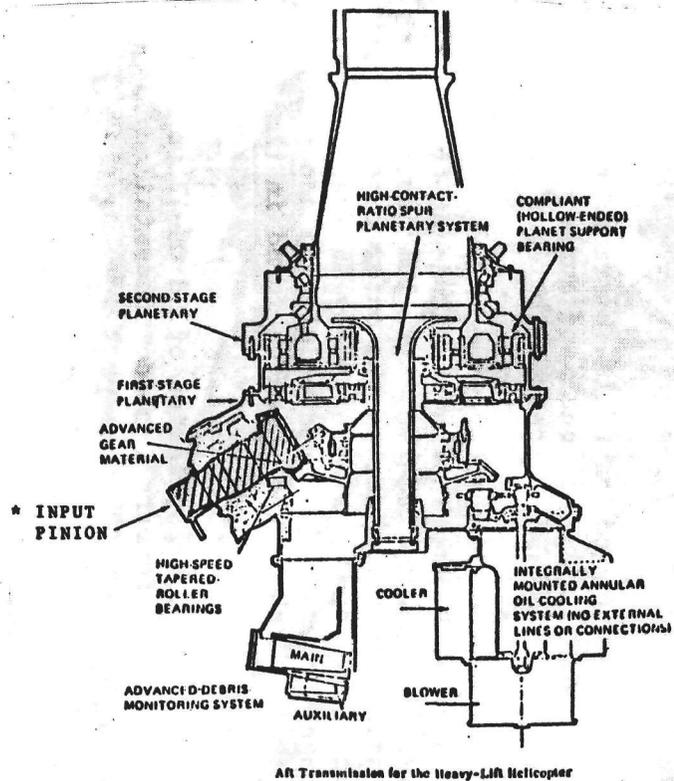
During the CH-47 engine and combining-transmission tests, four discrepancies were indicated and verified by teardown inspection. Two of the discrepancies were bearing outer-race spalls: one on the combining-transmission input-pinion-thrust ball bearing and the other on the engine-transmission input-pinion-support roller bearing. These spalls were indicated by 20 to 30-db peaks at the ball and roller pass frequencies over a point on the bearing outer race.

The third discrepancy was a worn input-pinion roller bearing in the combining transmission. This bearing had no localized surface defects such as pitting or spalling, but had 0.060-inch clearance between the rollers and races.

This defect was detectable by a 10-db drop in the amplitude of shaft frequencies and a 10-db rise in the cage frequencies. The fourth defect detected was occasional rotation in its liner of the outer race of this same worn bearing. The race slippage was detected by an event counter as a periodic burst of high-frequency (but undemodulated) acoustic energy. More detailed analysis of these tests can be found in reference 2.

Baseline data has been collected from a population of 38 CH-47 rotor transmissions to determine if a generic baseline (common unfailed signature for all serial-numbered units of the same part number) can be applied to both new and old components (TBO removals).

Using a generic baseline generated by 10 new aft transmissions, the demodulated high-frequency spectra of 11 aft transmissions that had been returned for overhaul were examined to determine how many 10-db (3 times baseline) spectrum exceedances each transmission had. Teardown inspection revealed that seven of the 11 transmissions had serious discrepancies while four were in good shape. Comparison of these results with the high-frequency-vibration analyses showed that none of the four good transmissions had any 10-db baseline exceedances while six of the seven defect cases had multiple baseline exceedances of 10 db or more, as shown in Figure B-7. The details of this program are contained in reference 3.



* During a two hour run at 100% load, a crack developed at the root of a tooth and propagated into the pinion shaft resulting in catastrophic failure.

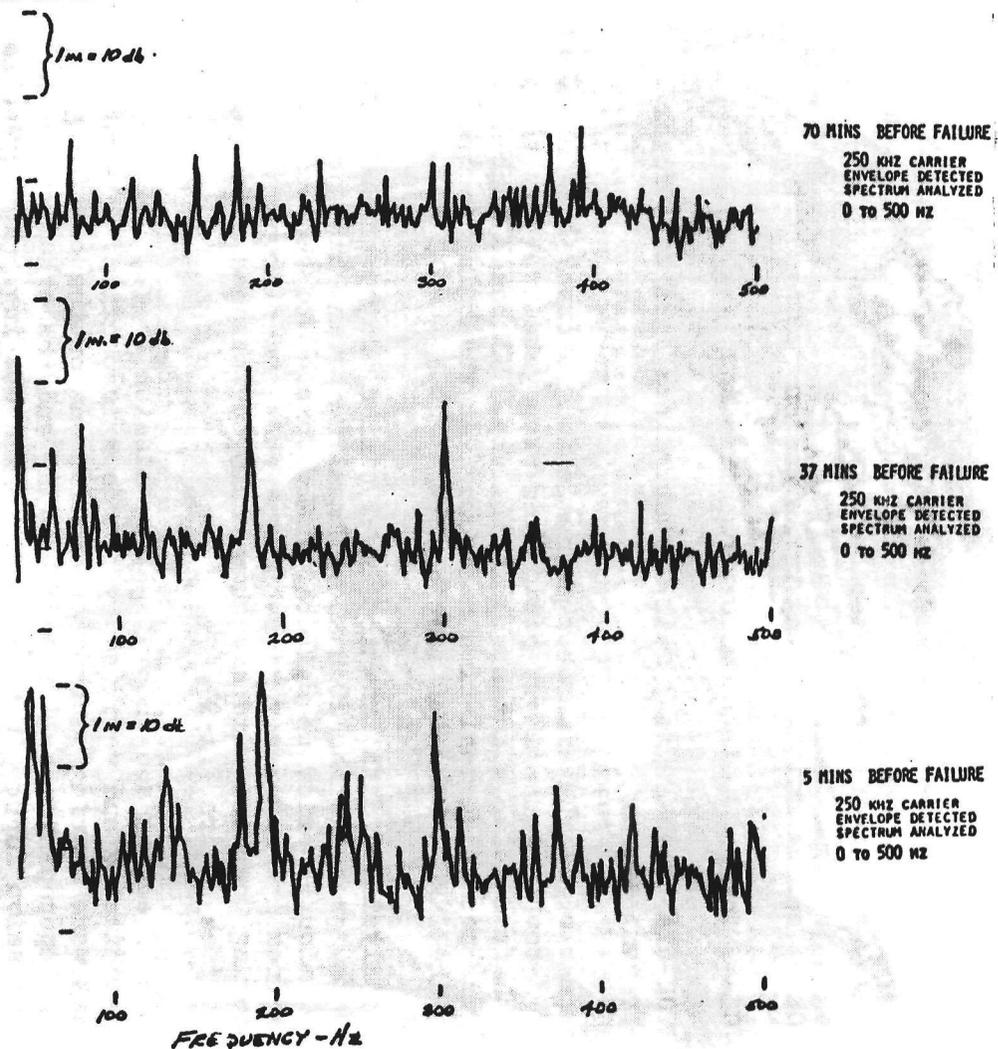


Figure B-6. HLH crack detection

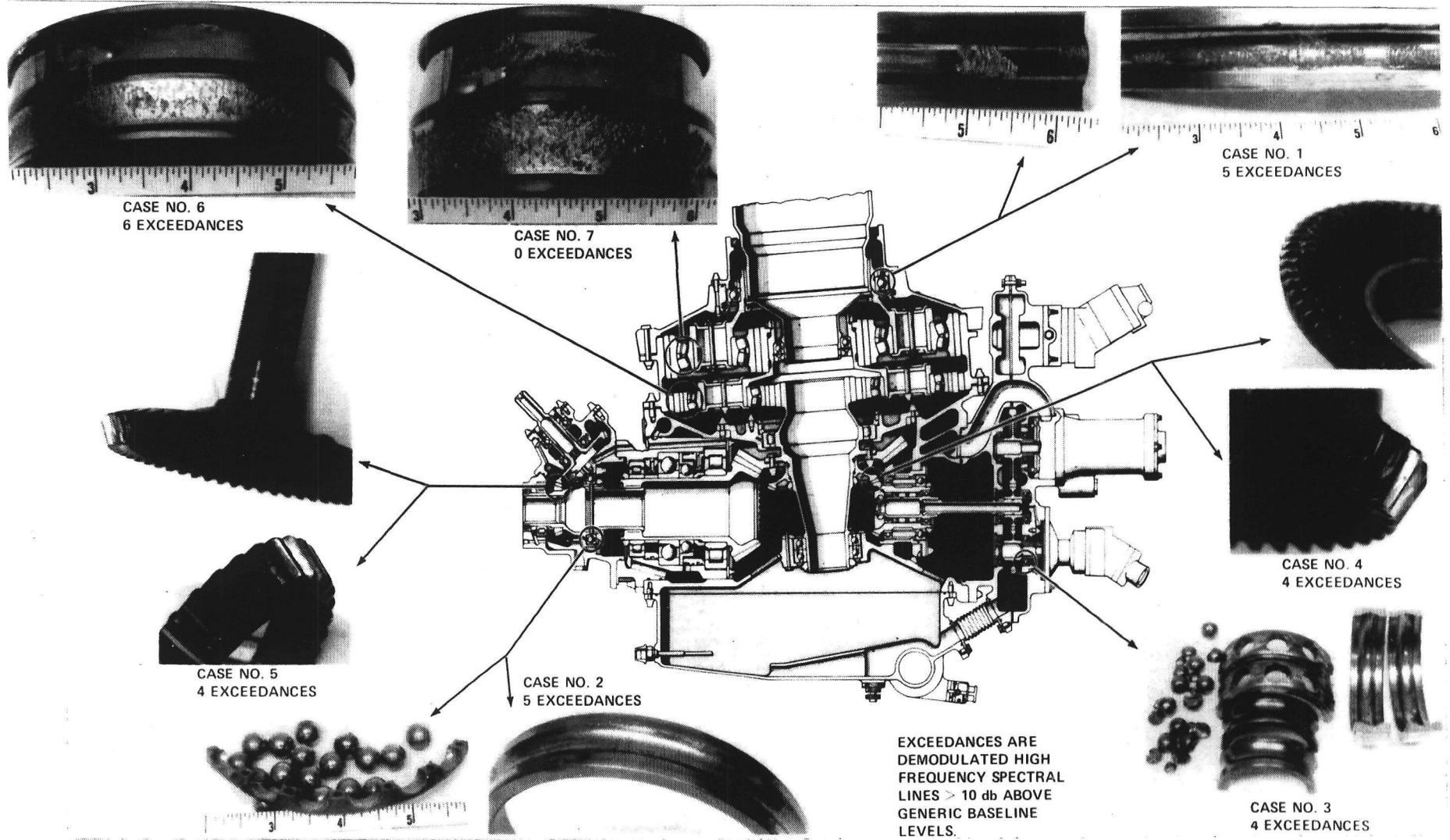


Figure B-7. CH-47 transmission condition assessment by high-frequency-vibration analyses

During the basic engineering development of the UTTAS helicopter, high-frequency-vibration data had been obtained periodically from the YUH-61A transmissions and gearboxes in test cells. No defects have been present during these data-collection efforts, so the data is being held for future generic baseline studies when data is available from a significant population of components. These tests are described fully in reference 4.

On-Aircraft Test Results

Also during basic engineering development of the UTTAS, data was recorded on the YUH-61A ground-test vehicle at the beginning and end of a 300-hour endurance test. Comparison of data taken at 250 hours with data taken at 50 hours indicated two discrepancies in the tail-rotor drive system.

These two discrepancies, one in a tail-rotor drive-shaft bearing and the other in the tail-rotor-gearbox input pinion, were both subsequently verified by teardown inspection. The discrepancy in the tail-rotor drive-shaft bearing was a partial loss of lubricant which allowed the cage to rub the outer race, thus generating highly abnormal cage-to-outer-race-frequency peak amplitudes.

The tail-rotor-gearbox fault was a crack in the shoulder of the outer race of an input-pinion roller bearing. Each time a roller passed the crack, the roller end would be nicked, thus generating dramatic peak amplitudes at the roller pass frequency over a point on the outer race.

On another occasion, abnormal amounts of debris were being generated in the UTTAS GTV main transmission. High-frequency-vibration instrumentation was installed to isolate the source of the debris and the data showed a 20-db abnormality symptomatic of a planet-bearing inner-race spall. The transmission was therefore removed and the defective planet bearing replaced prior to continuing the test.

Details of these test results are contained in reference 4.

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