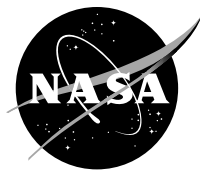


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## Abstract

U.S. Army goals for the Enhanced Rotorcraft Drive System Program are to achieve a 40 percent increase in horsepower to weight ratio, a 15 dB reduction in drive system generated noise, 30 percent reduction in drive system operating, support, and acquisition cost, and 75 percent automatic detection of critical mechanical component failures. Boeing's technology transition goals are that the operational endurance level of the helical face gearing and related split-torque designs be validated to a TRL 6, and that analytical and manufacturing tools be validated. Helical face gear technology is being developed in this project to augment, and transition into, a Boeing AH-64 Block III split-torque face gear main transmission stage, to yield increased power density and reduced noise. To date, helical face gear grinding development on Northstar's new face gear grinding machine and pattern-development tests at the NASA Glenn/U.S. Army Research Laboratory have been completed and are described.

## Introduction

The Boeing Company's development of helical face gear technology was structured in response to U.S. Army Enhanced Rotorcraft Drive System (ERDS) Program. The goals are advanced, high-potential drive system technology concepts offering performance improvements over conventional rotorcraft transmissions and drive system components. ERDS related development is being performed under a Technology Investment Agreement (TIA) between Boeing and the U.S. Army Aviation Applied Technology Directorate (AATD).

Earlier face gear investigations developed face gear tooth geometry and methods for tooth contact control, simulation of meshing and transmission error prediction for straight face

gears, as well as methods for tooth generation and determining limits of inner and outer radii (Ref. 1). Previous face gear grinding and test development work was also performed by Boeing, the University of Illinois at Chicago, Northstar Aerospace (Canada) Inc., a major producer of aerospace-quality gears, NASA Glenn, and the U.S. Army Research Laboratory, to allow the use of precision, high-strength, carburized and ground face gears in helicopter applications. This included testing carried-out prior to ERDS to investigate surface durability of AISI 9310 steel face gears (Ref. 2) and a proof-of-concept (POC) concentric split-torque, face-gear transmission as part of a DARPA-funded Technology Reinvestment Program (TRP). The POC tests demonstrated effective torque sharing and the potential for face gear transmissions to yield significant weight, cost, and reliability improvements over existing transmissions using spiral-bevel gearing (Ref. 3). Previous work also included full-scale split-torque demonstrator transmission tests and surface durability tests, which were performed using carburized, precision-ground AMS 6308 steel straight-tooth tapered face gears during the recent Boeing-AATD Rotorcraft Drive Systems for the 21<sup>st</sup> Century (RDS-21) Program (Ref. 4).

Helical face gear technology is being developed as part of the ERDS Program to enhance a high power density gear set which splits torque evenly and quietly along two load paths to demonstrate increased power density for the Boeing split-torque face gear concept. Full-scale system testing using helical face gears will be conducted to verify the endurance of an ERDS concept demonstrator transmission, and statistical data will be generated to substantiate helical face gear surface fatigue characteristics. In addition, low shaft angle helical face gears developed and applied for a tail rotor drive will be tested as part of the above endurance tests.

Face gears can be used in certain applications replacing spiral bevel gears, with significant advantage as they can be used in higher reduction ratio applications and unique configurations giving increased power-to-weight ratios. Also, the low-angle helical or straight-tooth face gear sets can be applied in designs requiring shaft angles as low as a few degrees, unlike spiral bevel gears.

A manufacturing machine and a method for precision grinding of helical-tooth face gears within AGMA equivalent Class 12-13 tolerances have been developed by Northstar Aerospace Canada of Milton, Ontario, working in conjunction with Boeing in Mesa, Arizona. This project, performed under the Boeing-AATD ERDS Program, follows the earlier development of a straight-tooth face gear grinding machine which produced gears for the DARPA Proof-of-Concept, DARPA 2828 HP Split-Torque, and Boeing-AATD Rotorcraft Drive System 21 Program. This paper presents an overview of the ERDS-developed method, which includes definition of surface points comprising the helical face gear and mating pinion tooth profiles, grinding of the helical tooth profiles, inspection, and static and dynamic contact patterns development, including helical face gear pattern development tests at the NASA Glenn Research Center in Cleveland, Ohio. The grinding process is based on the principal of continuous generation, allowing the production of high quality carburized and hardened helical face gears for use in current aerospace applications.

The face gear grinding methodology was primarily developed to meet the demanding requirements of high-power applications, including gear tooth case hardness, profile accuracy and surface finish. The most recent face gear grinding machine designed and built by Northstar is configured with additional machine functions for grinding helical face gears. These functions include the dressing of the grinding wheel and grinding of the gears using a continuous generation method developed by Northstar. Factors such as rotation, tilt and feed parameters for the grinding wheel, work table and dresser tool axis of motion, and specifications for computer numerical control (CNC) controllers, drive motors and measurement systems all had to be considered. One of the main objectives of the Northstar-Boeing helical face gear production work was to develop face gear grinding and coordinate measuring methods to form a closed-loop face gear manufacturing system. Accordingly, a coordinate measuring machine (CMM) process and tooth patterning procedure were also developed for helical face gears in conjunction with the grinding method. The finish-ground gear teeth are compared to theoretically-calculated surface points using a modified CMM inspection machine. Tooth contact analysis is performed in conjunction with inspection to develop the contact patterns. By utilizing computer-aided design (CAD) and other software packages, Northstar has developed modeling capability for face gear meshing analysis, face gear manufacturing analysis and determination of grinding wheel geometry.

To date, aerospace-quality face gears and pinions in various configurations have been produced by the Boeing-Northstar team using the described method, including face gears applied in the production Apache Block III 3400 hp main transmission and ERDS helical face gears referenced below.

A helical tapered face gear set design was developed for ERDS surface pitting fatigue tests conducted at NASA Glenn Research Center. Descriptions of the surface fatigue helical face gear designs, test apparatus and dynamic contact pattern development tests are included collectively in the paper. Also, helical face gears designed for the full-scale ERDS endurance transmission main stage and aft low-angle tail rotor drive are described, which will begin testing soon at Boeing.

The objective of the tooth surface fatigue tests is to determine the surface durability life of a helical face gear in mesh with a helical tapered involute pinion. Experimental fatigue tests performed at NASA included determination of the effect of shimming on helical face gear backlash and contact pattern. Contact pattern development tests were also performed to evaluate and refine a few pinion and face gear tooth design parameters. Accordingly, tooth crowning, profile and tip geometries were modified slightly to improve contact. As a follow-on to pattern development, primary surface pitting fatigue tests will soon begin on 36 sets of gears at three load levels. Helical face gear technology, test data and related manufacturing tools developed under the ERDS Program are planned to transition to the Boeing Apache Beyond Block III Program.

## Design Activities

Design activities began with specifying all component and system level design requirements for the helical face gear technology development tests. Design work was then performed on all helical face gear test components for ERDS surface fatigue profile development tests and primary tests and on all ERDS endurance transmission components for development tests, 200-hr endurance tests, 140 percent rotating bending fatigue (RBF) tests, tail rotor adapter gearbox tests, plus all custom test hardware. Endurance transmission system-level design work was performed to cover all assembly components and the gear configuration of helical tapered face gears, pinions and idlers in a split-torque arrangement which uses an in-line arrangement of the face gear teeth relative to pinion and idler teeth. Helical tapered face gears provide higher contact ratios compared to straight tapered face gears of equal face width, due to the helix angle involved. Helical gears are also quieter than straight-tooth gears. A view of the transmission configuration gear model is shown in Figure 1. A main cross-section of the transmission assembly is shown in Figure 2. Two helical tapered input pinions drive an upper and lower face gear simultaneously, one from either side of the gearbox. Three helical tapered idlers are used to direct the load fed to the lower face gear back to the upper face gear. The

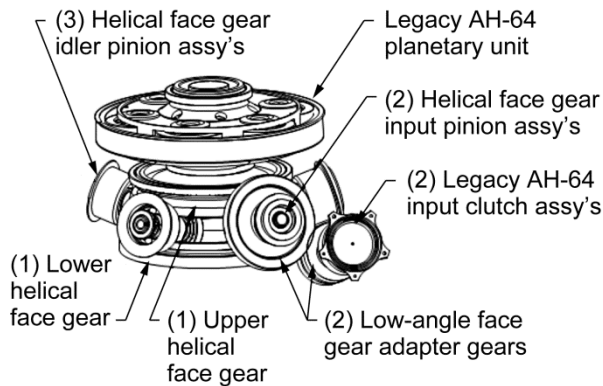


Figure 1.—ERDS endurance configuration transmission view of gear model arrangement.

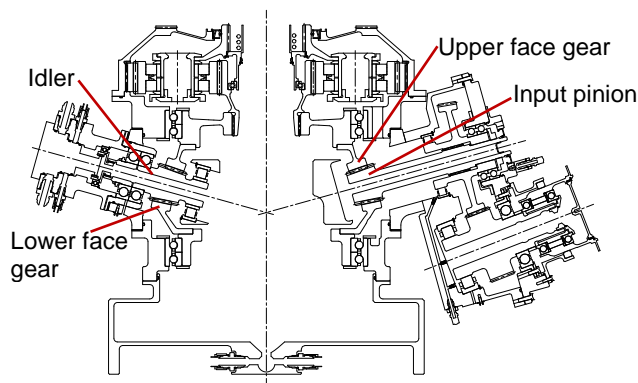


Figure 2.—Endurance configuration transmission design main cross section.

combined load on the upper face gear is used to drive an output planetary stage. The pinion shafts are cantilevered from a rear pivot location, allowing the pinions to float so that the input load is divided evenly to the upper and lower face gears.

The in-line design approach involved aligning the tooth centers of the helical tapered pinions and idlers with those of the helical-upper and lower face gears, so that the centers of the upper and lower face gear meshes were almost directly in line with each other across the pinion and idler shaft centerlines. A somewhat larger diameter lower face gear was used to help achieve this, since the input pinion uses a non-90° shaft angle. The in-line arrangement allows for a closer to equal torque split between the upper and lower pinion meshes, minimizes the net moments and separating loads reacted by the pinion and idler bearings, and shortens the face widths of the pinions and idlers due to less offset being present between the upper and lower meshes. The above design factors contribute to further weight reduction, as does the use of hybrid ceramic bearings on the face gear shafts. The idlers are straddle-mounted, with a duplex ball bearing and a roller bearing located on either side of the gear teeth. The face gears are overhung-mounted.

The upper face gear is splined to the sun gear of a current production AH-64A planetary stage. The lower face gear forms a ring, has no output spline and routes power directly from the

input pinions to the idlers. The reduction ratio of the face gear stage is 5.42 to 1. The ratio of the planetary stage is 3.88 to 1. The gears in the helical face gear test stage are being made from VIM-VAR Pyrowear 53 steel per AMS-6308, and they are carburized and ground, shot-peened and vibro-honed. The gears in the planetary and adapter gear stages were made from 9310 steel per AMS-6265.

A low-angle face gear set, which has a true spur gear as the pinion member, was designed for the input adapter stage of this transmission. The adapter stage enables the transmission to be installed in Apache A-model test rigs, and its reduction ratio is 1.62:1. The adapter face gears adapt the input shaft angle of the test stand with the pinion shaft angle, while also driving from behind and below the pinion shaft (from where the A model transmission first stage was previously located). Since the face gear stage replaces two of the A-model transmission stages, the adapter set was also needed to adjust the direction of rotation to allow installation in the A-model test stand. The above adapter gear stage entailed an intersecting axis design.

Additional types of helical tapered face gears and straight tapered face gears were developed as part of this ERDS project. The gear designs involve low-angle, skew-axis face gears. These low-angle face gears will be applied inside a Tail Rotor Adapter Gearbox (TRAG) to drive a simulated tail rotor during tests with the endurance transmission. A view of the low-angle skew axis face gear designs inside the TRAG gearbox is shown in Figure 3, and the arrangement of the endurance transmission-TRAG gearbox assembly models is shown in Figure 4. The three gears of the skew axis TRAG set are comprised of one helical tapered face gear at the input, one standard helical idler and one straight tapered face gear at the output. The output shaft will drive a dynamometer from the same location and angle as the A-model Apache transmission tail rotor output. The TRAG adjusts the shaft locations and angles, from where it's driven at the input from the aft idler of the face gear stage, to where it drives the dynamometer from the output. The segments of the endurance tests involving the TRAG gearbox will be run to assess aft helical idler loading characteristics as it's driven from the lower helical face gear and in turn drives the TRAG input shaft.

The low-angle face gear designs involved with the above endurance transmission input stage and TRAG gearbox were developed because of their inherent advantages over spiral bevel gears (or other gear types) for the applications described. In addition to the rather low shaft angles accommodated, their geometry provides full-line contact capability for these low-angle applications. This and the ability to use ball bearings having lower thrust capacities reduced configuration size and weight for the designs.

Similar to the endurance transmission, all gear, shaft, housing and other structural components are being manufactured by Northstar for the TRAG gearbox.

Design of the lubrication and cooling system shared by the endurance transmission and TRAG gearbox was part of configuration design development.

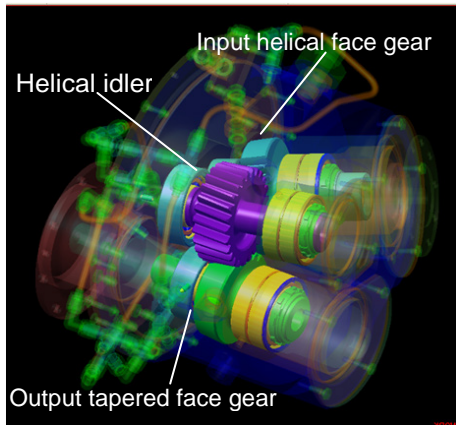


Figure 3.—CAD models of low-angle face gears inside tail rotor adapter gearbox.

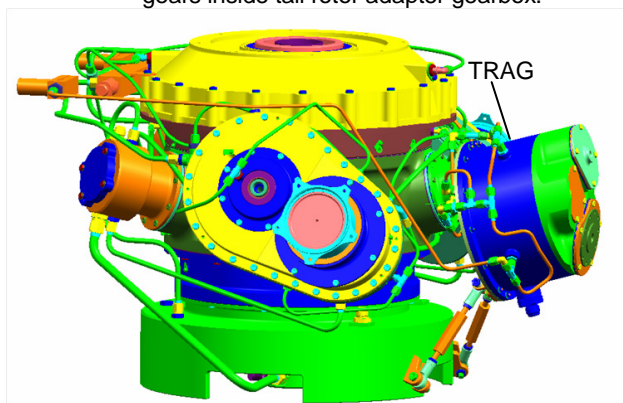
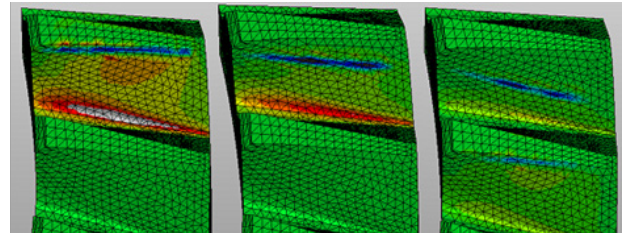


Figure 4.—CAD models of endurance transmission with tail rotor adapter gearbox attached (shown on right).

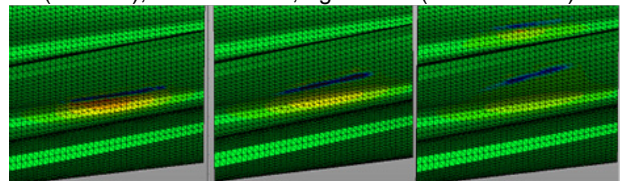
## Analysis Activities

Analysis and analytical tool development activity was also performed as a key part of ERDS helical face gear technology development. Initial analysis included loads determination and all component life and stress calculation work supporting the design of all gear and bearing components. Gear stresses were determined relative to AGMA allowables for bending stress, contact stress and tooth scoring. A life analysis was then performed for the bearings using the A.B. Jones computer program. Critical sections stress analysis of the housings and shafts as well as Nastran finite element (FEA) stress-deflections analysis of the housings, gear webs and gear rims were also carried out.

A dynamic frequency analysis was performed on all test gear-shaft components using a three-dimensional solid model of each component in MSC Patran software. The undamped natural frequencies for the first through fourth resonant modes were calculated in Nastran. The frequency results were determined from averaging the data sets from three analyses involving different combinations of element type, size, number and number of nodes for each frequency mode. The results were used in minor design modifications and will be used as reference during tests.



(a) Max principle stress on NASA helical gear, left:  $t=0$  (HPSTC), middle:  $t=0.5$ , right  $t=1.0$  (one tooth rev).



(b) Max principle stress on NASA helical pinion, left:  $t=0$  (LPSTC), middle:  $t=0.5$ , right  $t=1.0$  (one tooth rev).

Figure 5.—Abaqus non-linear contact analysis model of ERDS helical face gear and pinion, run using Abaqus FEA solver.

Tooth geometry was determined and kinematics of meshing was evaluated for the helical tapered pinions, idlers and face gears used in the split-torque face gear arrangement. In conjunction with this, analytical studies investigated torque splitting characteristics of helical tapered pinions in mesh with two helical face gears, load sharing among multiple helical idlers and the effects of tail-rotor and accessory power taken from an idler.

Analytic tools were developed to support ERDS helical face gear design and manufacture. A viable tool for the determination of helical face gear tooth contact stress and root bending stress was developed using the contact capability of the Abaqus/Standard FEA solver in conjunction with the Abaqus/CAE pre-processor and post-processor. Abaqus non-linear contact analysis models were produced for the helical surface fatigue and 200-hr endurance test face gears, and finite element analysis (FEA) was then conducted for these to allow determination of areas of maximum stress and distribution of tooth loading as the gears roll through mesh under applied loads (Fig. 5). Finite element model mesh densities were refined for the Abaqus analyses to allow the most accurate determination of helical face gear contact stresses (least error) relative to AGMA contact stresses seen for similar-geometry standard helical gears, while not requiring extensive amounts of run time. Similarly, the Abaqus contact FEA tool for predicting helical face gear tooth bending stress was validated by comparison to AGMA calculations, combined with past Boeing experience, helical gear analysis results obtained using non-contact FEA and correlation with experimentally determined results from the previous Technology Reinvestment Program (TRP) proof-of-concept (POC) tests and RDS-21 slow roll tests.

Also, manufacturing analysis tools were developed in support of helical face gear design and fabrication for surface fatigue tests and endurance transmission 200-hr and 140 percent load RBF tests, including tests of the tail rotor



adapter gearbox. These additional tools are described in the Manufacturing Development Activities section below.

Helical face gears, pinions and idlers were designed as part of an in-line endurance transmission configuration and a tail rotor adapter gearbox assembly developed during ERDS. NASA helical face gear test sets were also designed for surface fatigue evaluations. Helical face gears being developed and refined under ERDS will yield power density increases and noise level reductions. Operational benefits already determined for the split-torque, concentric face gear transmission will be enhanced by the development and use of helical face gears in the multi-mesh application involved. Low-angle helical and straight-tooth face gears, both skew and intersecting axis, provide significant advantages over the use of other gear types for low-angle single and multi-mesh applications.

## Manufacturing Development

Manufacturing development for this program was performed in the Northstar Aerospace Gears and Transmission manufacturing facility in Milton, Ontario Canada. This facility has the capability to produce precision face gears for aerospace applications and is where all the experimental hardware was manufactured for the numerous Boeing, AATD and DARPA programs. The face gear manufacturing capability Northstar Aerospace developed not only involved the design and development of a precision face gear grinding capability, but also included all the key elements of gear design through manufacture to ensure that a viable production capability was created. These key elements, along with advanced machining development, included mathematical and CAD modeling, software development, heat treatment, non-destructive testing, and development and measurement of face gear tooth contact patterns and profiles.

The establishment of this successful production capability has produced hardware for the AH64 Apache Improved Drive System qualification program which utilizes a face-gear split-torque design. Capacity expansion for AH64 Block III face gear production required Northstar Aerospace to further develop its manufacturing capability, which has included the design and manufacture of a second-generation face gear grinding machine. This machine, designated MKII (Company name) (Fig. 6), was designed with key enhanced features as compared to those of the first MKI (Company name) machine. These features, although primarily aimed at production process enhancements, afforded Northstar Aerospace the opportunity to expand the manufacturing scope of the machine for the continued development of face gears.

Prior to building the MKII machine, manufacturing development considered face gears meshing with parallel and tapered involute pinion gears only. With the manufacture of the MKII machine, the manufacturing process for helical face gears meshing with helical tapered pinions could be explored. Under the ERDS program, various sizes and configurations of helical face gear sets have been produced in quantity for test and evaluation activities.



Figure 6.—MKII face gear grinding machine.



Figure 7.—Grinding wheels configured for face gear grinding.

The MKII face gear grinding machine utilizes an abraable grinding wheel approximately 13 in. in diameter from which is cut a single-start thread form (Fig. 7).

The machine has ordinarily eight axes of motion which are under CNC. Each axis is a fully-closed loop enabling the CNC to closely monitor the actual position of each axis to provide the greatest possible precision. The grinding wheel form, combined with five axes of continuous CNC machine motion, generates the required face gear tooth profile during the grinding process. Figure 8 shows the MKII machine after completion of the grinding cycle for an ERDS lower face gear.

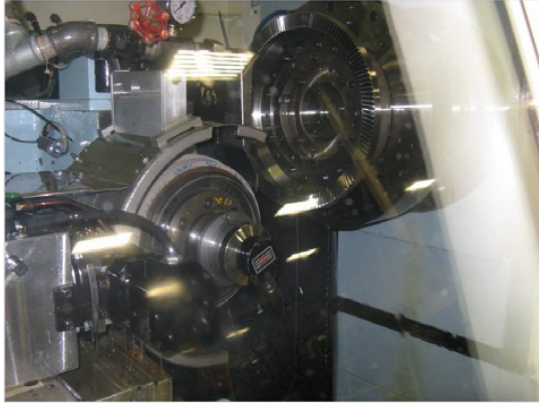


Figure 8.—MKII helical face gear grinding.



Figure 9.—Grinding wheel with dressing system.

As the grinding wheel wears and becomes loaded with material due to grinding, the process is periodically interrupted. The grinding wheel is then dressed (reshaped) using a five-axis dressing system. Each time that the grinding wheel is dressed, its diameter is reduced and the spiral of the thread form changes. These changes are compensated for by custom CNC programs and software developed by Northstar Aerospace. This software ensures that the transition from wheel dressing back to gear grinding is seamless and all dimensional compensation is automatic. Figure 9 shows the grinding wheel with the dressing tool to the left. Both the grinding wheel and dresser are controlled by CNC to dress the thread form on the grinding wheel.

The five-axis CNC motion used to generate the gears on the MKII adds an additional axis of motion to that of the MKI machine (Fig. 10). The addition of this axis significantly increased the design and complexity of the machine, though

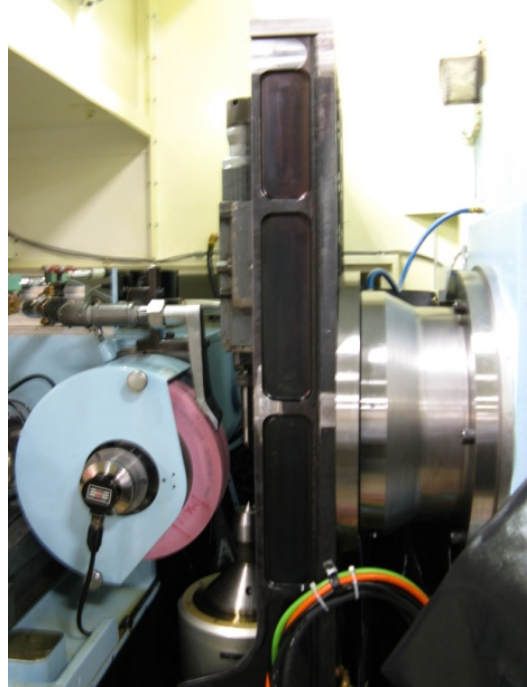


Figure 10.—MK II configured with additional axis.

necessary to further refine the manufacturing process. Both machines produce face gears and pinion gears for the Block III program in the same manner; however the MKII machine has the capability to grind more face gear variants and further optimize manufacturing cycle times.

The machine also has a ninth CNC axis which is installed when grinding the helical tapered pinions and removed for face gear grinding. This axis attaches to the machines fixed horizontal work spindle providing an angularly variable vertical work spindle for pinion gear grinding.

Supporting technology was developed to enable the grinding of face gears on both the MKI and MKII machines. The development of an effective method of analysis of face gear geometry was critical for determining baseline gear grinding wheel geometry, machine motion and dimensional data for CMM inspection.

Accordingly, these technologies were also developed for helical face gears and proved to be significantly more complex when considering a tapered pinion and a shaft angle not equal to 90°. Figure 11 shows a theoretical segment of a helical face gear and three teeth of the mating pinion gear. This dynamic modeling is used as a starting point to determine initial gear tooth form geometry, the grinding wheel profile and machine motion.

Figure 12 shows an actual helical face gear and pinion under lightly-loaded conditions. This testing is used to physically determine the contact patterns of the gears as they mesh and rotate, and is used to determine that the gears mesh as designed. Areas where fouling and undesirable contact between the gears occurs are particularly scrutinized. Changes are made to the gear tooth forms until the patterns are optimized.

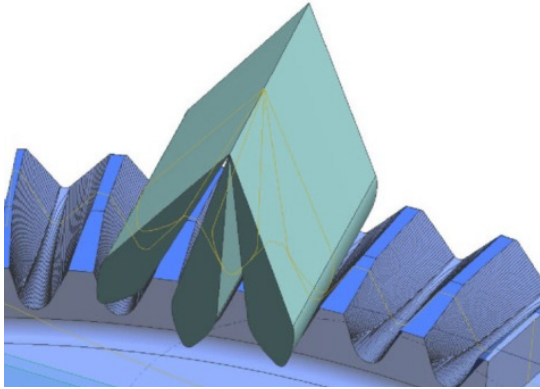


Figure 11.—Helical face gear meshing analysis

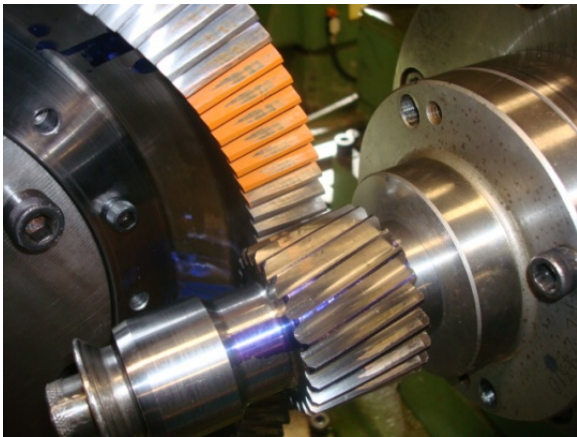


Figure 12.—Helical face gear contact pattern analysis.

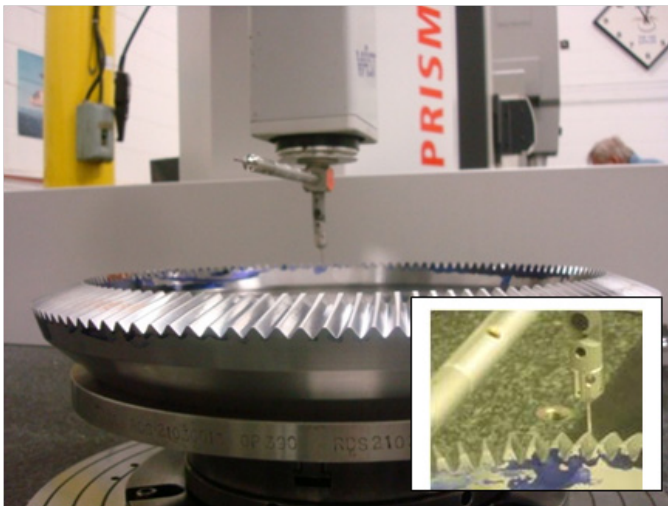


Figure 13.—Helical face gear meshing analysis.

Figure 13 shows a helical face gear being measured on a CMM. This measurement dimensionally inspects each flank of a selected number of gear teeth. A rectangular grid of 63 data points is predefined and used to measure and compare the form of each tooth flank. Additionally the gear is inspected for tooth-to-tooth spacing accuracy and run out.

Figure 14 shows the results of the helical face gear inspection performed on the CMM. This chart shows each flank of one gear tooth and compares 63 measured points to the corresponding programmed points. This inspection closes the loop on the manufacturing development process for face gears, providing valuable data which is used to optimize the gear meshing requirements and manufacturing process.

The challenges of producing helical face gears were numerous due to the helix angle of the face gear. Early analysis of the helical gear mesh created numerous questions in respect to the ability to grind helical face gears, even with the additional CNC axis of motion added to the MKII machine. Concerns arose with the amount of helix angle and therefore the angle was limited to 10°. This was due to the complexity of defining a grinding wheel profile that in practice would not clip or foul during grinding, and therefore produce a suboptimal tooth form.

The grinding wheel size and form for producing face gears with no helix angle has been refined by Northstar Aerospace to provide a proven consistent production method. The grinding wheel profile provides single-start thread and grinds both sides of the face gear flanks simultaneously. The challenge with helical face gears was to be able to do the same. Many approaches were considered and evaluated including grinding using multi-start grinding wheels, different diameter grinding wheels and single-flank grinding with different grinding wheel forms.

These approaches were considered during the design of the MKII machine, and where possible, the capability was built into the machine. Once the machine was built, the most practical concepts were tested on the ERDS test gears as they were being prepared for heat treatment (carburizing and hardening). Initially, due the fact that the helical face gear teeth (tapered pinion) have a different helix on each flank, alternative grinding wheel profiles were used to grind each flank separately. As the development process continued, the profile and machine motion were modified until the same profile could be used to grind both flanks simultaneously. This method was initially applied only to gears for NASA and only for pre-heat-treatment preparation. For post-heat-treatment grinding, the accuracy requirement for the grinding process is much greater, and initially, the two profile single-flank grinding approach was used. As the process development continued, the grinding wheel profiles were optimized to the point where one profile could be used to grind each flank, but separately, utilizing different machine motion.

Helical face gears were successfully produced for the ERDS program. The degree of complexity, due to the gear design of helical face gears meshing with helical tapered pinions, added an extreme challenge to optimize the manufacturing process. This complexity allowed only a 10° helix angle to be considered for this program. The complexity of the design also caused developmental issues in defining the gear tooth geometry and CMM inspection data; however these were successfully resolved.

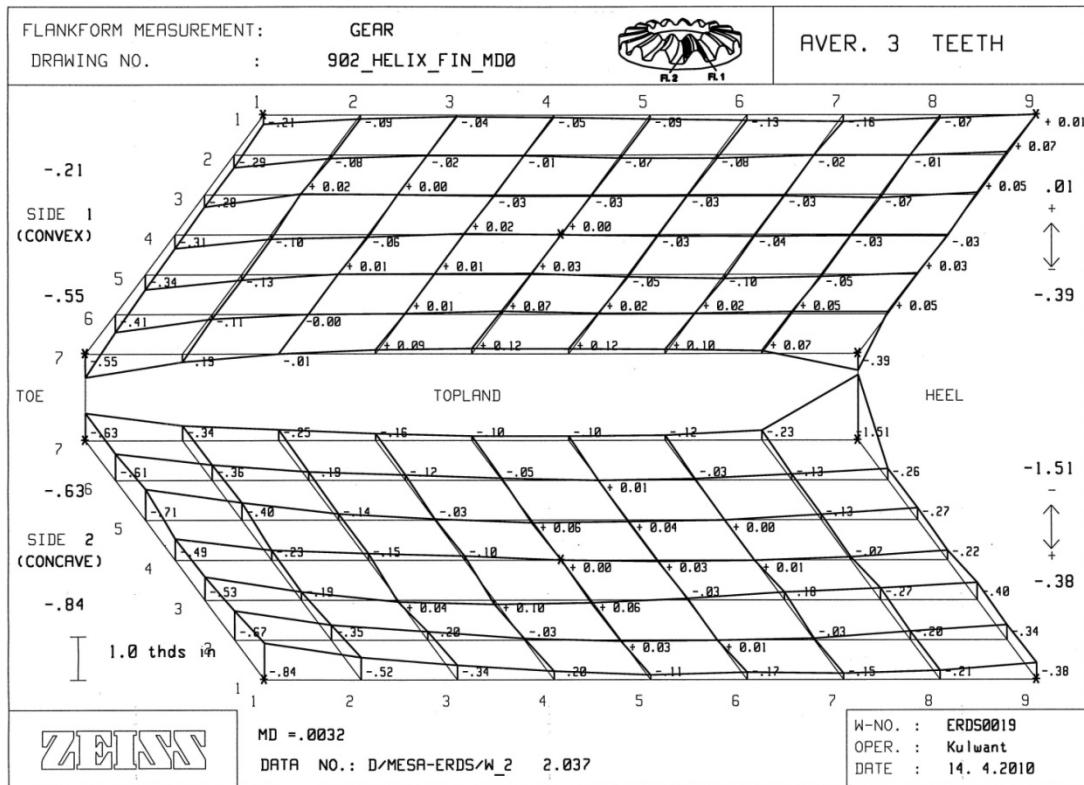


Figure 14.—Helical face gear CMM inspection chart.

The results of this and prior development efforts have been recognized through the award of patents by both the United States and Canada for the face gear grinding machines and their capabilities. Patent applications are pending in other jurisdictions. Continuing development work by Northstar Aerospace may become subject to further patent protection.

## Test Development

Experiments were performed in the NASA Glenn spiral-bevel gear/face gear test facility. An overview sketch of the facility is shown in Figure 15(a) and a schematic of the power loop is shown in Figure 15(b). The facility operates in a closed-loop arrangement. A pinion drives a face gear in the test (left) section. The face gear drives a set of helical gears, which in turn, drive a face gear and pinion in the slave (right) section. The pinions of the slave and test sections are connected by a cross shaft, thereby closing the loop. Torque is supplied in the loop by physically twisting and locking a torque in the pre-load coupling on the slave section shaft. Additional torque is applied through a thrust piston (supplied with high pressure oil), which exerts an axial force on one of the helical gears. The total desired level of torque is achieved by adjusting the oil supply pressure to the piston. A 100-hp DC drive motor, connected to the loop by V-belts and pulleys, controls the speed as well as provides power to overcome friction. The facility has the capability to operate at 750 hp and 20,000 rpm pinion speed. A torque meter in the loop on the test side measures torque and

speed. The facility is also equipped with thermocouples, oil flow meters, pressure transducers, accelerometers, shaft tachometer counters, and shutdown instrumentation to allow 24-hr unattended operation.

The test gears and facility bearings and gears were lubricated and cooled by a pressurized oil system. The lubricating fluid used was a synthetic-base helicopter transmission oil conforming to the DOD-L-85734 specification. The test helical pinions and face gears were lubricated by jets which radially directed oil into the roots of the teeth on both the into-mesh and out-of-mesh sides. The nominal oil supply pressure was 80 psi and the nominal flow rate was 1.0 gpm for both the test section and slave section. Oil inlet temperature was set at 85 °F. An external vacuum pump connected to the oil tank worked as a scavenge system to remove the oil from the test gearboxes and bearing cavities and direct it to the sump. Also, the oil system was equipped with an oil-debris monitor as well as a three-micron filter.

The design parameters for the helical pinions and face gears used in the tests are given in Table I. A photograph of the test specimens is shown in Figure 16. The set was primarily designed to fail in surface pitting fatigue mode. The set had a reduction ratio of 3.842:1. The set also had a diametral pitch of 10.723 teeth/in., roughly similar to previous face-gear endurance tests (Ref. 5). The face width of the face gears was 0.5 in. The face width of the pinions was 0.7 in, significantly greater than the face gear to allow for backlash adjustment and optimization of tooth contact. The helix angle was 10°. The

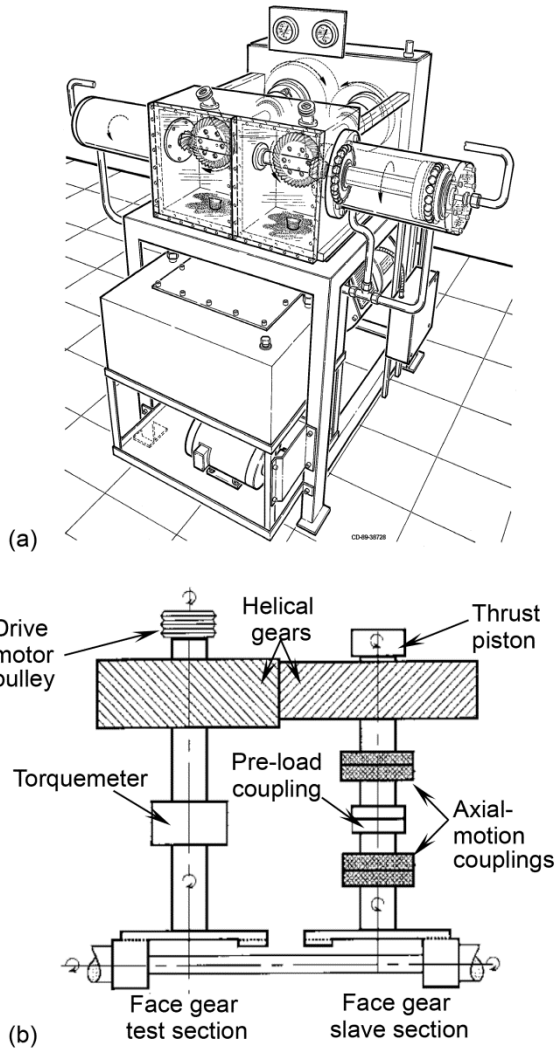


Figure 15.—NASA Glenn spiral-bevel-gear, face-gear test facility. (a) Overview of facility. (b) Schematic view.

TABLE I.—TEST GEAR DESIGN DATA.

AGMA quality .....	12
Number of teeth; pinion, gear.....	19, 73
Diametral pitch.....	10.723
Pressure angle (deg) .....	27.5
Shaft angle (deg) .....	90.0
Helix angle (deg).....	10.0
Face width (in.); pinion, gear .....	0.7, 0.5
Hardness (Rc); case, core .....	62, 38
RMS surface finish.....	16
Material .....	X53 steel

shaft angle was 90° to accommodate the facility. The pinions were slightly tapered, similar to the previous designs, which allow the independent setting of backlash for the multiple pinions and idlers in the split-torque transmission application (Ref. 6).



Figure 16.—Test gears.

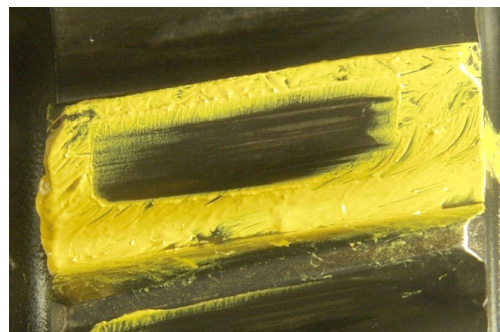
The helical pinions and face gears were made from carburized and ground vacuum induction melted-vacuum arc remelted (VIM-VAR) Pyrowear 53 steel per AMS 6308 using standard aerospace practices. At 6000 lb-in. face gear torque, the calculated AGMA contact stress index was 250 ksi and the calculated AGMA bending stress index was 72 ksi using approximate spur gear calculations per AGMA (Ref. 7).

Previous studies showed that proper pinion and face gear installation is a criteria for successful operation (Refs. 2 and 5). Face gear adjustment had a significant effect on both pattern and backlash. Moving the face gear out-of-mesh increased backlash and moved the contact pattern from heel to toe. On the other hand, moving the face gear in-to-mesh decreased backlash and moved the contact pattern from toe to heel. Moving the pinion in-to-mesh decreased backlash, but had a relatively small effect on the face gear tooth contact pattern for the range of adjustments used. Moving the pinion out-of-mesh increased backlash, and also had a relatively small effect on the face gear tooth contact pattern. As expected, the contact pattern on the helical pinion tooth moved from heel to toe as the pinion was moved out-of-mesh (backlash increased), and from toe to heel as the pinion was moved in-to-mesh (backlash decreased). However, since the pinion tooth width was wider than the face gear tooth width, the patterns still remained on the tooth. Thus, adjusting the pinion position was an effective way of adjusting backlash without severely affecting the contact pattern.

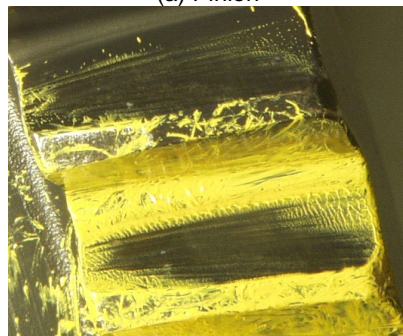
The installation procedure for the gears tested was then defined as follows. First, the test-side helical pinion and face gear were installed in the facility (with no cross shaft connected to the pinion). Backlash measurements and no-load contact pattern checks were taken for the mesh as described above. A contact pattern biased slightly toward the heel on the face gear and a backlash of 0.006- to 0.010-in. was required for this trial. The slight bias of pattern was required since the pattern shifted slightly toward the toe when full load was applied. If necessary, the face gear shim was first adjusted to achieve the proper contact pattern, and then the pinion shim was adjusted to achieve the proper backlash. This process was then repeated for the slave-side helical pinion/face-gear mesh. Figure 17 shows

an acceptable no-load contact pattern. After proper shimming was achieved, the cross shaft was installed. Marking compound was then re-applied to all the pinions and gears and a loaded static roll test was performed. This was done by applying a moderate torque in the loop (through the load piston), manually rotating the complete assembly, and photographing the resulting contact patterns. Figures 18 to 20 show tooth contact pattern checks for a loaded static roll test at three different torque levels.

Tests were performed on four sets of helical tapered pinions and helical face gears. Table II gives the test conditions and preliminary results. The initial tests (sets 1 and 2) were run at 2300 rpm and 6000 lb-in., face-gear speed and torque. 8.2 million (M) face-gear cycles were completed, resulting in no fatigue failures and moderate tooth wear. Sets 3 and 4 were subsequently installed on the right side. The speed was reduced to 2200 rpm to reduce vibrations caused by near-resonance operating conditions. The load was increased to 7200 lb-in. face-gear torque. This resulted in pinion tooth pitting fatigue failures. Figure 21 shows the pinion condition for set 4. A pit was found on one pinion tooth after approximately 17.5 M face-gear cycles. The pit occurred near the pitch line and slightly biased toward the heel of the tooth. Set 3 had a similar pinion tooth fatigue failure after approximately 7.7 M face-gear cycles, which resulted in a tooth fracture of the pinion tooth.

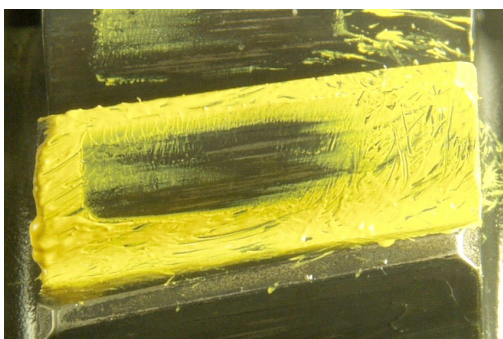


(a) Pinion

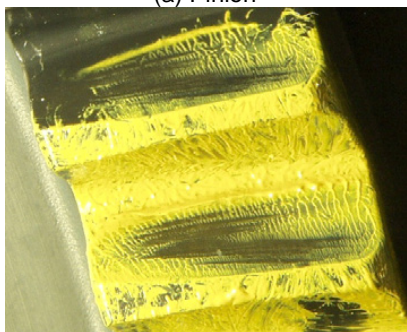


(b) Face gear

Figure 18.—Typical loaded contact pattern check, ~1100 lb-in gear torque.

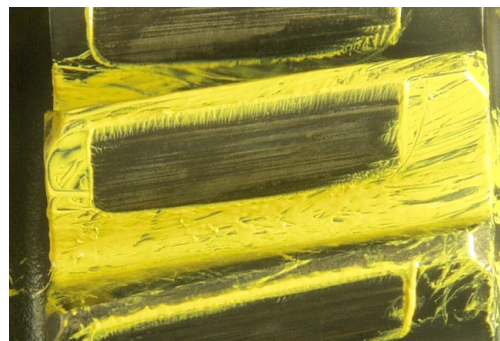


(a) Pinion

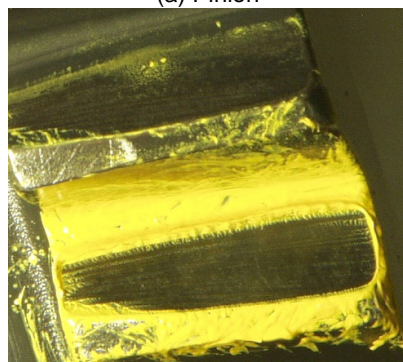


(b) Face gear

Figure 17.—Typical contact pattern check, hand resistance.

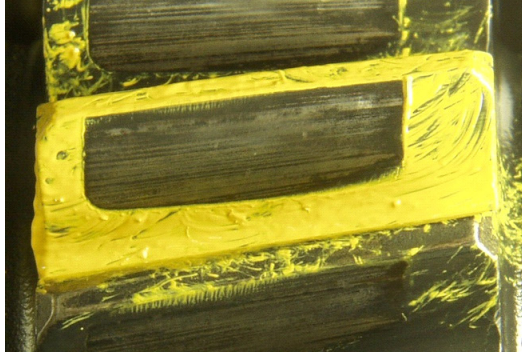


(a) Pinion

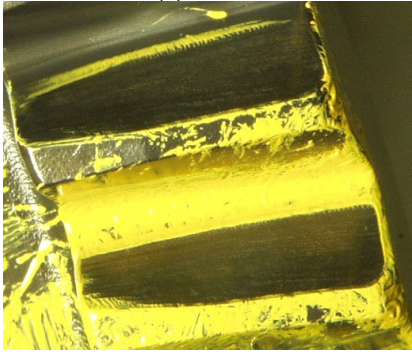


(b) Face gear

Figure 19.—Typical loaded contact pattern check, ~2100 lb-in gear torque.



(a) Pinion



(b) Face gear.

Figure 20.—Typical loaded contact pattern check, ~4300 lb-in. gear torque.

TABLE II.—PRELIMINARY TEST RESULTS

Set	Gear speed (rpm)	Gear torque (lb-in.)	Gear cycles	Side	Results
1	2200, 2300	6000, 7200	46.1	Left	Suspended, moderate wear
2	2200, 2300	6000, 7200	20.9	Right	Suspended, moderate wear
3	2200	7200	7.7	Right	Pitted/fractured pinion tooth
4	2200	7200	17.5	Right	Pitted pinion tooth

After pinion tooth pitting failures of sets 3 and 4, set 2 was reinstalled on the right side and continued run with set 1 at 2200 rpm and 7200 lb-in. face-gear torque. The sets were suspended after 46.1 and 20.9 M face-gear cycles on sets 1 and 2, respectively. Figure 22 shows the condition of set 1. For this set, micropitting started along the pitch on the pinion after around 12 M face-gear cycles. However, the micropitting did not propagate, as shown in Figure 22(a). Moderate wear occurred on the helical pinion and the meshing face gear (Fig. 22(b)).

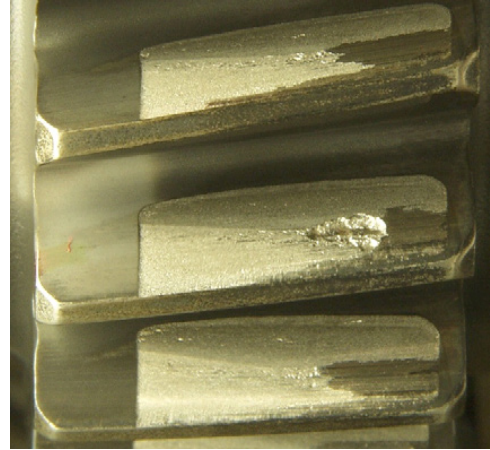
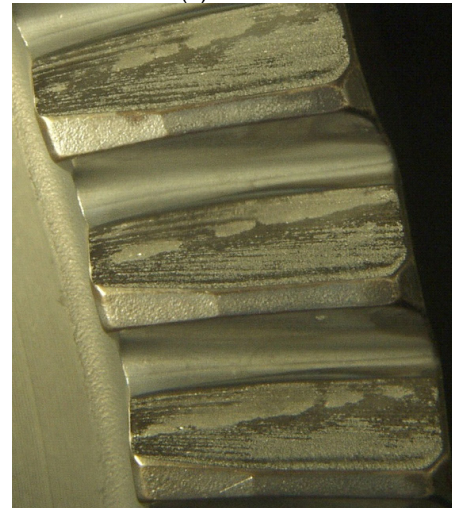


Figure 21.—Pinion tooth pitting fatigue failure, set 4, after 17.5 M cycles at 2200 rpm, 7200 lb-in face gear speed and torque.



(a) Pinion



(b) Face gear

Figure 22.—Gear condition after inspection, set 1, after 46.1 M face-gear cycles.

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<b>14. ABSTRACT</b> U.S. Army goals for the Enhanced Rotorcraft Drive System Program are to achieve a 40 percent increase in horsepower to weight ratio, a 15 dB reduction in drive system generated noise, 30 percent reduction in drive system operating, support, and acquisition cost, and 75 percent automatic detection of critical mechanical component failures. Boeing's technology transition goals are that the operational endurance level of the helical face gearing and related split-torque designs be validated to a TRL 6, and that analytical and manufacturing tools be validated. Helical face gear technology is being developed in this project to augment, and transition into, a Boeing AH-64 Block III split-torque face gear main transmission stage, to yield increased power density and reduced noise. To date, helical face gear grinding development on Northstar's new face gear grinding machine and pattern-development tests at the NASA Glenn/U.S. Army Research Laboratory have been completed and are described.					
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