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Enhanced Automated Spiral Bevel Gear Inspection

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Space Administration

US ARMY
AVIATION
SYSTEMS COMMAND

ENHANCED AUTOMATED SPIRAL BEVEL GEAR INSPECTION

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SUMMARY

An enhanced manufacturing technique for the design and in-process inspection of spiral bevel gears, utilizing a computer-controlled multi-axis coordinate measuring machine, has been demonstrated at Sikorsky Aircraft in a Manufacturing Methods and Technology program sponsored by the U.S. Army AVSCOM Propulsion Laboratory, Cleveland Ohio.

The technique uses a Zeiss universal measuring machine in conjunction with an enhanced Gleason Works software package that permits rapid optimization of spiral bevel gear tooth geometry during initial tooth form development, and more precise control of the tooth profile in production. The process involves three-dimensional mapping of spiral bevel gear teeth over virtually their entire working surface, using the Zeiss machine, and quantitative comparison of surface coordinates with nominal master gear values at some 45 grid points on the tooth surface. In addition this technique features a means for automatically calculating corrective cutting and grinding machine settings, involving both first and second-order changes, for controlling the tooth profile to within specified tolerance limits.

This enhanced positive control method eliminates all of the subjective decision making involved in the tooth patterning method, which compares contact patterns obtained when the gear set is run under light brake load in a rolling test machine. The inclusion of the second-order change calculation in the automatic correction process, demonstrated in this program, reduces the manufacturing/inspection time by 1.72 hours per gear compared to the baseline process which included first-order changes only.

PREFACE

This report presents the results of a follow-on program to develop an enhanced inspection method for spiral bevel gears. The initial program covered the definition and development of a final inspection method utilizing a multi-axis coordinate measuring machine and featured automatic calculations of corrections for first-order grinding machine settings. The program reported on herein involves the extension of the method to include second-order machine corrections.

The work outlined herein was performed under NASA contract NAS3-25961 with funding provided by the U.S. Army Aviation Systems Command (AVSCOM). The technical monitor for the project was Timothy Krantz of AVSCOM's Propulsion Directorate at the NASA Lewis Research Center, Cleveland, Ohio.

This program was conducted by Sikorsky Aircraft, Division of United Technologies, under the technical direction of Harold Frint, Program Manager, and Charles Isabelle, Chief of Design and Development of Transmissions. Principal investigator was Warren Glasow, Senior Manufacturing Research Engineer.

Acknowledgement is gratefully made to Theodore Krenzer, Robert Hotchkiss and John Thomas of the Gleason Works, Rochester, New York, for their support and assistance.

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INTRODUCTION

Proper and reliable service from a pair of spiral bevel gears can be obtained only when they are manufactured accurately and mounted into precision-machined gearbox housings that position and maintain the driving and driven gear members in a specified three-dimensional relationship throughout their useful life. Gears produced on existing gear-generating and grinding equipment will run smoothly and carry the design load without distress if tooth spacing is maintained, the teeth are machined concentric with the rotating axis, and the tooth profile contour is controlled so that maximum tooth pair conjugation is achieved when operating under full load conditions.

Since it is impractical to design and fabricate gear teeth and gear mounts that are free from deflections when operating under load, most high-power gears are designed with tooth profile modifications along the tooth face and in the profile direction to compensate for load-induced deformations and tooth errors, and to prevent load concentration at the ends or tips of the teeth which could result in excessive wear, scoring, or even tooth breakage. This is as true for spiral bevel gears as it is for spur and helical gears.

The elemental conformity inspection of tooth profiles that is commonly performed on spur and helical gears, however, is not practical for spiral bevel gears because the size and shape of a bevel gear tooth varies along its face width instead of being constant as in the case of a spur gear. Prior to the development and implementation of the automated inspection process, spiral bevel gears were inspected on a specifically designed Gleason test machine, shown in Figure 1, which provided a rotating test of the gear pair simulating no-load operation under simulated gearbox mounting conditions. Tooth contact patterns under these rotating conditions could be observed by painting the teeth with a marking compound, similar to jeweler's rouge, and running the gears with their mating master control gears for a few seconds in the gear tester with a light brake load. Because of the compound curvatures inherent in the spiral bevel gear tooth form and the profile modifications designed into the teeth, these gears typically exhibited a localized composite tooth contact pattern, which, ideally, should spread out under full load, filling the working area of the tooth with some easing off at the end areas of contact. The size, shape, and position of this tooth bearing were a gross indication of the tooth topology both up and down the tooth profile and lengthwise along the tooth face. Typical tooth contact patterns are shown in Figure 2. If the resultant tooth contact pattern did not duplicate, within limits, the shape, location, and percentage of contact of the master gear set, run under identical conditions, the gears were disassembled for regrinding. A gear engineer analyzed the pattern and made a judgment as to what machine setup changes were required to improve the pattern.

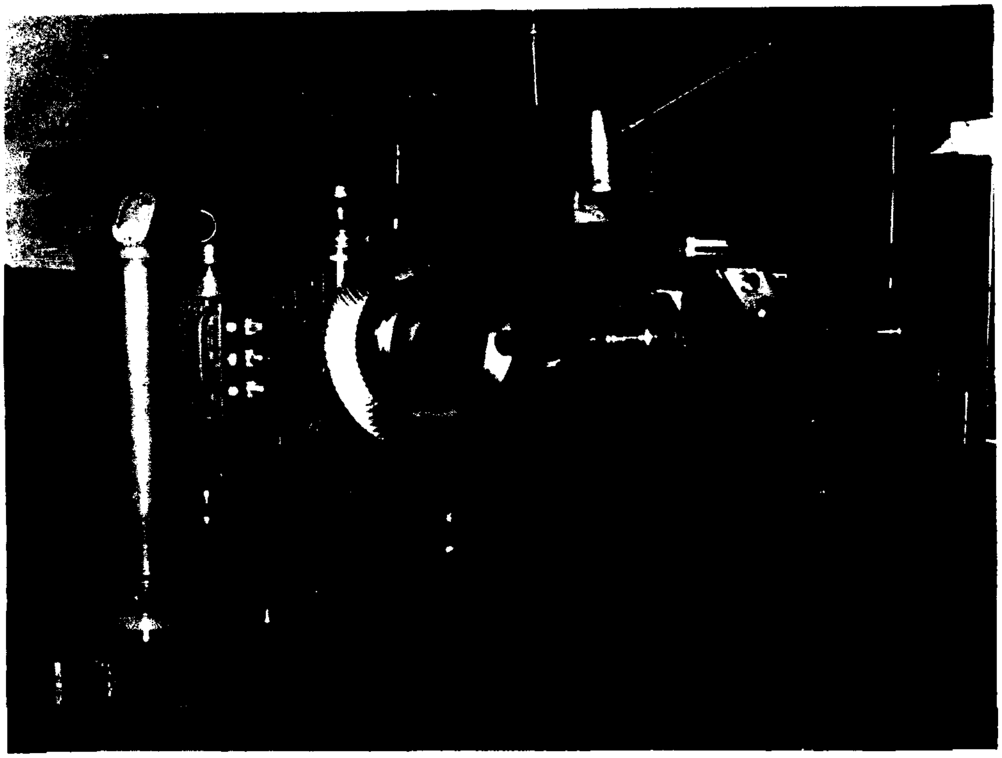


Figure 1 - Gleason Test Machine

When necessary, the pinion was reground to the new adjusted settings and the testing process repeated. The number of iterations necessary to obtain a satisfactory gear profile depended upon the skill and experience of the test machine operator or the gear engineer. This judgment process was probably the weakest link in gear tooth pattern development, even with experienced machine operators.

This method of manufacturing primary drive spiral bevel gears required an experienced and qualified organization. It has been said that the development of a spiral bevel gear is more of an art than a science. This expression is based on the requirement for skilled bevel gear machine operators who use their background experience to evaluate the position, shape, and contour of the gear tooth contact pattern produced by the rolling test in the test machine. The machine operator's judgment is relied upon to determine what grinding machine setting or combination of settings is best used to correct an undesirable feature in the test pattern.

Gleason gear grinding machine settings involve first, second, and third order changes. First-order changes affect heel and toe position of the contact pattern as well as top and flank position. These changes are used in the final positioning of the tooth contact pattern. Second-order changes include bias (diagonal movement) changes, profile changes, and wheel diameter changes. Third-order changes include wheel dresser offset changes and heel and toe length changes. There are approximately 14 machine settings that are used by the machine operator in changes that affect the shape and position of the gear tooth pattern. Second and thir(-order changes require a calculation of values, using formulas provided by the

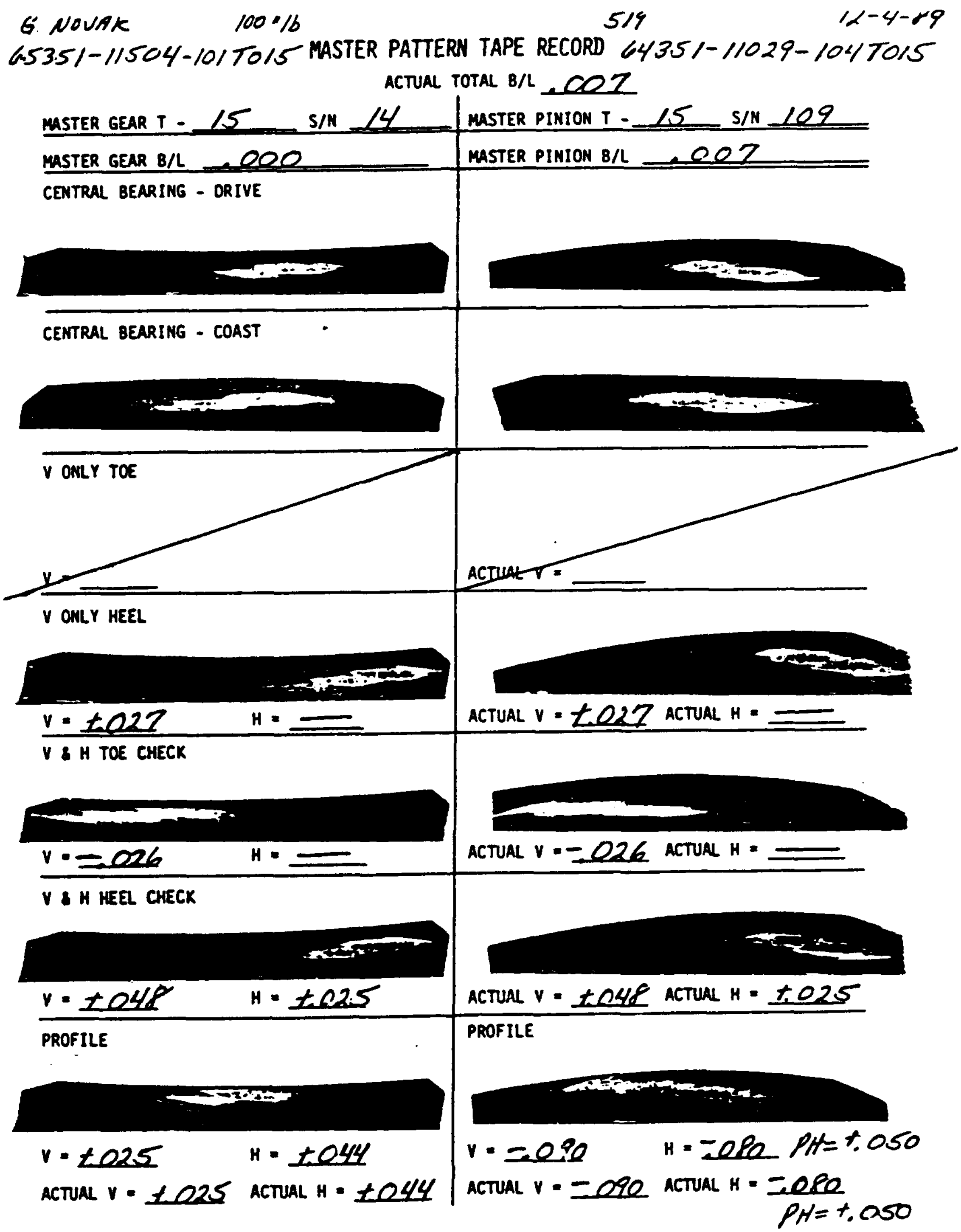


Figure 2 - Typical Gear Contact Patterns

Gleason Works, by a gear engineer who is consulted prior to making these changes.

The quality control process described above had certain inherent disadvantages. First, the acceptance or rejection of a production gear was based upon a visual comparison of tooth contact patterns. Not only the size of the pattern, but its shape and location, was significant. Acceptance limits for these features were difficult to define quantitatively, therefore the accept/reject decision became a subjective one and was subject to the human frailties of the operator. Second, the size, shape, and location requirements of the tooth contact pattern were peculiar to each gear mesh and gearbox mounting and no particular area, shape, or position could be considered universally ideal. Third, since the tooth contact is localized, and tested under a very light brake load, it was necessary to determine not only that satisfactory contact patterns were obtained when the gears were mounted in their equivalent running position in the gear tester but to what extent this pattern could be changed by axial and radial movements of the pinion axis with respect to the gear axis, that would move the pattern to the limits of the tooth contact zone. This is known throughout the industry as the V and H check. By comparing patterns at these extreme V and H settings, a cursory check on lengthwise and profile curvatures was maintained. It should be noted, however, that, in some cases, particularly with small cutter geometry, it was impossible to extend the contact to the extreme corners of the tooth by this method.

It is apparent from the above discussion that a definite need existed for a more definitive and objective way of determining whether a bevel gear profile is acceptable, and what specific changes are necessary in the grinding machine settings to most efficiently bring an errant pattern situation under control before it gets too far out of hand. It is well known how important it is to control the tooth profile on highly loaded gears to within rather narrow limits. A tooth profile with excessive profile or spiral angle error could result in concentrations of load that could cause scuffing, pitting, or even tooth breakage.

In June, 1982, Sikorsky Aircraft was awarded a contract (NAS3-23465) under the sponsorship of U.S. Army AVSCOM to define and develop an automated inspection and precision grinding procedure for spiral bevel gears utilizing a three-coordinate measuring machine. This effort was completed in August, 1985 and was considered highly successful. This improved inspection system is now in place at Sikorsky Aircraft and is gaining wide acceptance throughout the industry. A unique feature of this technique is that corrective first-order grinding machine settings are rapidly and automatically calculated for controlling the tooth profile within specified tolerance limits.

The objective of the present program, reported on herein, is to demonstrate and validate the theoretical corrective matrix for both first-order and second-order machine change capability. This enhanced correction process will result in a minimum of machine adjustments in a production mode producing a higher quality gear with a further reduction in inspection time.

This is the second step toward the ultimate closed-loop automated interface system linking the automated coordinate measuring machine with the new generation of CNC spiral bevel gear grinders such as the #463 CNC Gleason Grinder and the Phoenix 400PG Gleason gear grinder.

THE AUTOMATED INSPECTION PROCESS

The objective of this improved gear measurement system is the quantitative comparison of the actual manufactured spiral bevel gear surface topology with an idealized surface, in this case represented by a "hard" master control gear. The computer-controlled measuring machine uses the XYZ coordinates of this nominal or reference surface as a guide for probing and comparing the actual production gear tooth profile.

Differences between the production gear tooth surface coordinates and the nominal values, stored in the measuring machines computer, are displayed either as topographical plots or digital printouts. See Figures 3 and 4. The corrective first-order machine setting changes are automatically calculated and printed out as shown in Figure 5.

Universal Multi-Axis Coordinate Measuring Machine

When checking the topology of a three-dimensional curved surface, such as a spiral bevel gear tooth flank, using computer-controlled multi-axis measuring machines, the following requirements must be met:

- The nominal or reference surface must be expressible either as a mathematical model or as a matrix of discrete coordinate values representing the desired surface.
- The actual surface must be measurable with precision accuracy in a reasonable period of time.
- Quantitative comparison of the actual and nominal tooth surfaces should be possible.
- The causes of any deviations from nominal values must be interpretable to permit corrective grinding machine setup when the deviations exceed specified tolerance limits.

The Zeiss™ Universal Measuring Machines, either Model UMM 500 or Model ZMC 550, satisfied the above requirements and offered an effective solution to the problem of spiral bevel gear tooth measurement. The ZMC 550, recently purchased by Sikorsky to satisfy BLACK HAWK/SEAHAWK production requirements, is an accurate multi-axis coordinate measuring machine with an integrated Hewlett-Packard computer system that permits unlimited spatial probing in any of the three orthogonal directions. This machine, in conjunction with a sophisticated Gleason/Zeiss three dimensional software package, provides a distinct and quantitative means of measuring and mapping three dimensional surface contours. In order to accommodate the complex surface of the spiral bevel gear tooth, a precision indexing table is used as the fourth axis in the gear measuring programs. The computer program package for gear measurement permits the determination of the face profile coordinates of spiral bevel teeth using as many as 243 (9X27) probe points on the tooth surface and a

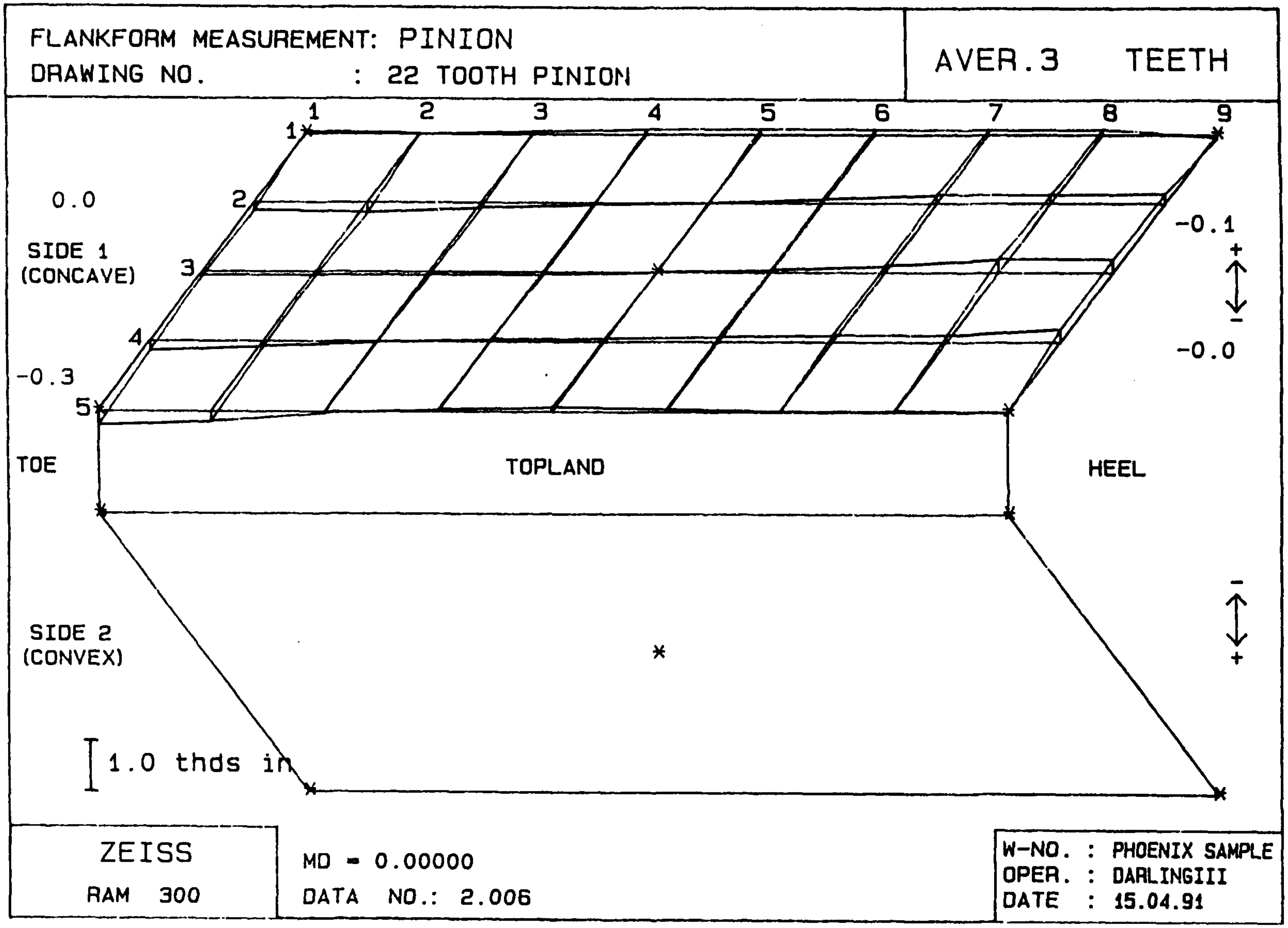


Figure 3 - Typical 3-D Plot from Zeiss

C	L	AVERAGE	S	MIN	MAX
1	1	0.00005	0.00011	-0.00009	0.00010
1	2	-0.00016	0.00010	-0.00029	-0.00010
1	3	-0.00009	0.00009	-0.00019	-0.00002
1	4	-0.00019	0.00007	-0.00028	-0.00014
1	5	-0.00028	0.00007	-0.00037	-0.00023
2	1	-0.00000	0.00010	-0.00013	0.00005
2	2	-0.00021	0.00008	-0.00032	-0.00017
2	3	-0.00008	0.00008	-0.00018	-0.00003
2	4	-0.00011	0.00008	-0.00021	-0.00005
2	5	-0.00020	0.00005	-0.00026	-0.00017
3	1	0.00006	0.00008	-0.00005	0.00010
3	2	-0.00010	0.00006	-0.00018	-0.00008
3	3	-0.00008	0.00006	-0.00016	-0.00003
3	4	-0.00002	0.00004	-0.00007	0.00001
3	5	-0.00003	0.00005	-0.00009	0.00001
4	1	0.00010	0.00006	0.00001	0.00013
4	2	-0.00004	0.00005	-0.00010	-0.00002
4	3	-0.00006	0.00003	-0.00011	-0.00005
4	4	0.00004	0.00004	-0.00001	0.00007
4	5	0.00003	0.00004	-0.00001	0.00006
5	1	0.00011	0.00005	0.00005	0.00015
5	2	-0.00001	0.00001	-0.00003	-0.00001
5	3	0.00000	0.00001	-0.00003	-0.00001
5	4	0.00006	0.00002	-0.00002	0.00006
5	5	0.00008	0.00003	0.00004	0.00010
6	1	0.00010	0.00002	0.00007	0.00012
6	2	0.00008	0.00000	0.00006	0.00007
6	3	0.00005	0.00000	0.00003	0.00003
6	4	0.00010	0.00001	0.00007	0.00009
6	5	0.00004	0.00003	0.00000	0.00006
7	1	0.00010	0.00003	0.00005	0.00011
7	2	0.00017	0.00003	0.00012	0.00017
7	3	0.00013	0.00003	0.00010	0.00015
7	4	0.00013	0.00002	0.00009	0.00014
7	5	0.00000	0.00003	-0.00005	0.00002
8	1	0.00011	0.00003	0.00007	0.00012
8	2	0.00016	0.00004	0.00011	0.00019
8	3	0.00027	0.00003	0.00023	0.00028
8	4	0.00013	0.00005	0.00006	0.00016
8	5	0.00002	0.00006	-0.00004	0.00007
9	1	-0.00006	0.00004	-0.00011	-0.00004
9	2	0.00020	0.00004	0.00015	0.00022
9	3	0.00026	0.00004	0.00022	0.00030
9	4	0.00026	0.00006	0.00019	0.00031
9	5	-0.00002	0.00005	-0.00006	0.00003

Figure 4 - Digital Printout from Zeiss

```
GLEASON MACHINE CORRECTIONS
SUMMARY NO.:   179961        PART NUMBER: PHOENIX SAMPLE
DATE/OPER.: 15.04.91 DARLINGIIIACTUAL FILE NUMBER:  6
DATA DOWNLOADED ON: 17.01.199 DIFF. ANGLE THEOR.: -9.249
                 662 MACHINE SETTING CHANGES
                    FIRST, AND 2ND ORDER
                 THEORETICAL PINION CONCAVE
```

CURRENT GRINDING WHEEL SPECIFICATIONS

	I.B.	O.B.
PRESSURE ANGLE	21.712 deg	13.928 deg
PROF. RADIUS OF CURV. ..	815.61 mm	95.64 mm

RADIAL DISTANCE	0.203 mm
OUTSIDE PRESSURE ANGLE (abs.)	13.908 deg
OUTSIDE PROFILE RADIUS OF CURV.(abs.) .	95.637 mm
WHEEL DIAMETER	0.002 mm
MACHINE ROOT ANGLE	0.000 deg
SLIDING BASE	0.000 mm
RATIO OF ROLL	0.00000
CENTER ROLL POSITION	0.174 deg
WORK HEAD OFFSET	0.00 mm
MACH CNTR TO CROSS PT.	0.000 mm
MODIFIED ROLL 2C	0.0424
MODIFIED ROLL 6D	0.0057

AVERAGE ERRORS	SIDE 1	SIDE 2
PRESSURE ANGLE	1.31 min	0.00 min
SPIRAL ANGLE	0.60 min	0.00 min
WARP FACTOR	0.16 min./mm	0.00 min./mm
SUM OF ERRORS SQUARED BEFORE CORR. ...		0.00000072
SUM OF ERRORS SQUARED FIRST ORDER ...		0.00000031
SUM OF ERRORS SQUARED SECOND ORDER ...		0.00000921
MEASURED TOOTH THICKNESS		0.000 mm

Figure 5 - Corrective First-Order Changes

point-by-point comparison with the stored nominal reference values. Generally a grid network of 5 lines and 9 columns, however, are sufficient to map the tooth surface.

The automatic measuring and data processing system presently installed at Sikorsky consists of several instruments (Figure 6), which are controlled by a central computer. The system shown includes a Hewlett-Packard 300- series Desk Top Computer, a Zeiss™ Universal Measuring Machine ZMC 550, a Hewlett-Packard Winchester Drive, an X-Y Plotter and a Impact Line Printer. The pinion and gear setup on the Zeiss™ ZMC 550 is shown in Figures 7 and 8.

Figure 6 - Zeiss™ ZMC-550 Measuring Machine

Determination of Nominal Values

The simplest method for determining the nominal reference points on a spiral bevel gear tooth flank is by digitization of the Reference Master Control Gear. The measuring machine is made to probe actual points on the flank of the master gear tooth, as described below, for storage on a data disc. This disc, in effect, becomes the unvarying "soft" master in this improved inspection method. Gleason/Zeiss software permits rapid generation of an evenly distributed point network over the tooth profile after calculating the corner points and defining the network density. Care is taken to exclude the edge breaks or corner rounding when establishing the corner points. The vector of the surface normal at each network point is determined mathematically from several automatically probed points in the near vicinity of the specified point (see Figure 9). These normalized values are stored on the disc along with the coordinate values. A network of 45 points (a 9 by 5 matrix) was

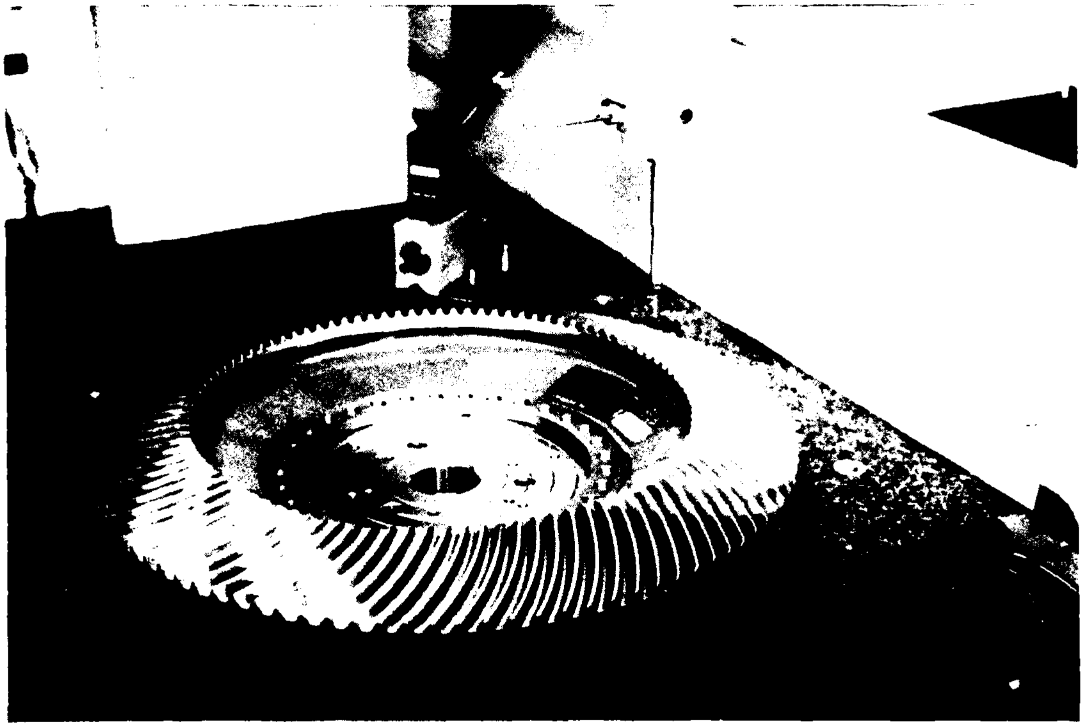


Figure 7 - Gear Set-Up on ZMC-550

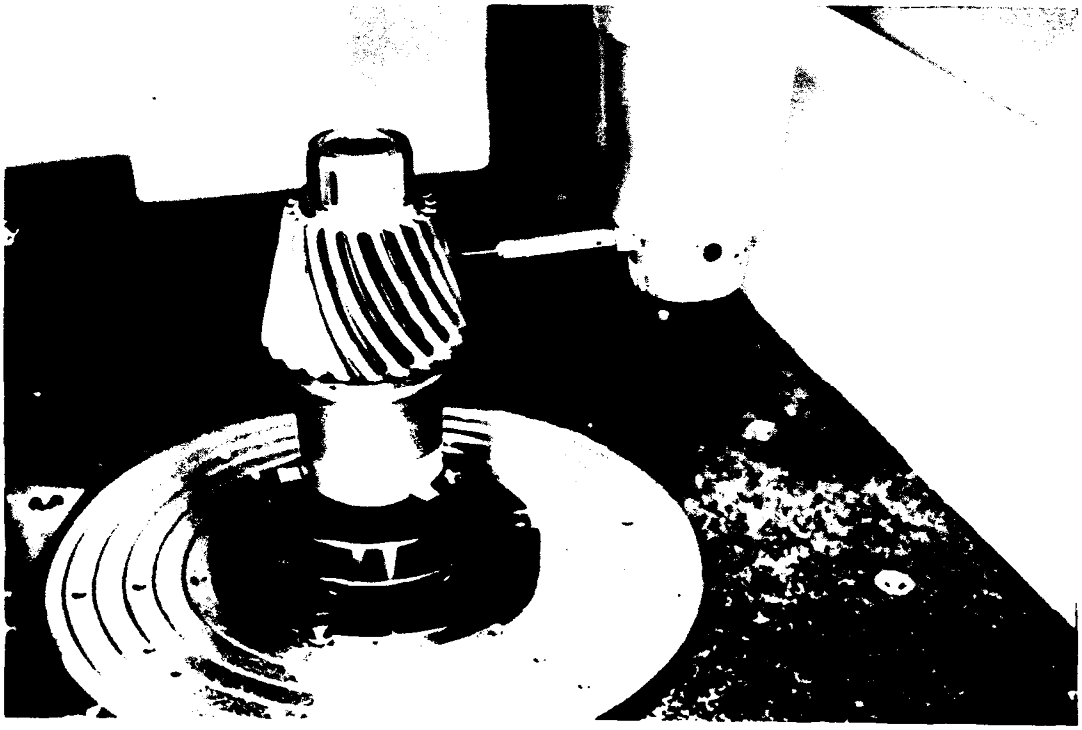


Figure 8 - Pinion Set Up on ZMC-550

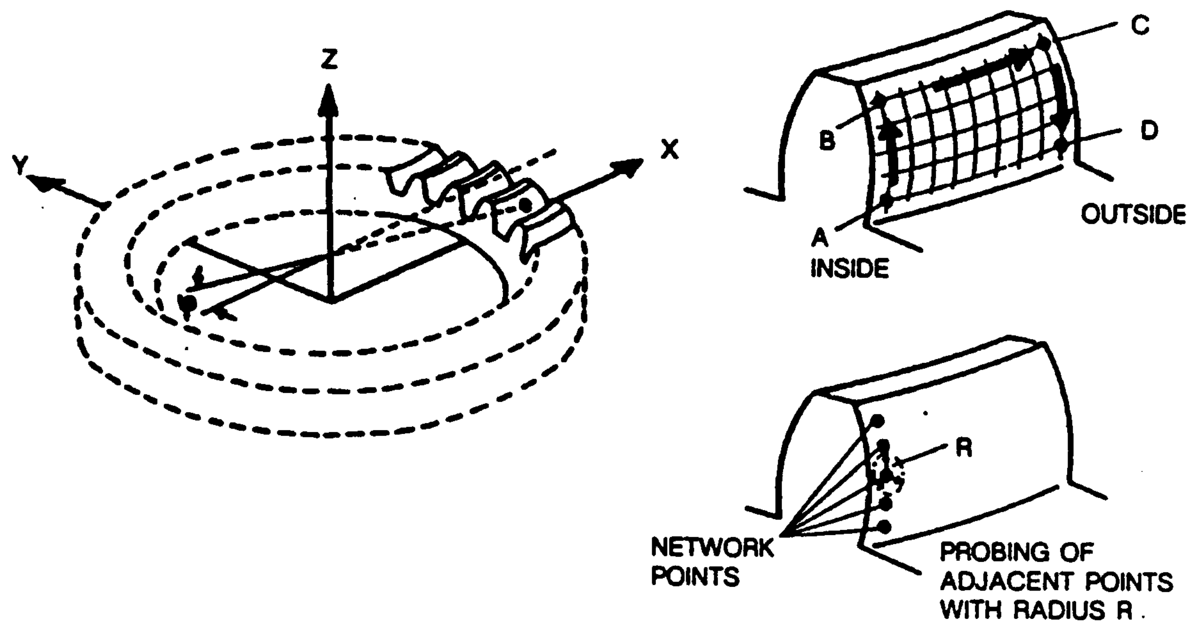


Figure 9 - Generation of Network Points

chosen because it was felt that this size grid would provide an adequate map of the tooth surface without resorting to time-consuming linear interpolation. Finer or coarser grids are, of course, possible.

Even though spiral bevel gears possess a high degree of geometric complexity, it was reasonable to expect that the nominal surface could also be generated numerically by computer simulation of the manufacturing process. This, in fact, was accomplished by the Gleason Works. Gleason provides the software that converts final grinding machine settings, as reflected on a Gleason Grinding Summary, (See Figure 10), into theoretical profile coordinate points which can also be stored in the ZMC 550 computer as nominal values. This method provides a more theoretical baseline for the measured master gear values, which themselves are subject to manufacturing errors. These theoretical points are used in the Gleason G-AGE™ Program to calculate the corrective matrix.

The Measurement Process

The inspection process consists of setting up the gear in the Zeiss™ machine and automatically probing the surface at the previously- -determined 45 network point locations. To accomplish this, the gear is mounted on the coordinate measuring machine rotary table with its axis parallel to the Z axis of the machine (see Figures 6, 7, and 8), care being taken not to deform it while clamping. Part alignment is achieved by bringing the probe into contact at a series of points

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT — **GLEASON SUMMARY**

GROUND GENERATED SPIRAL BEVEL SUMMARY NO. # 06342C SHEET 1 OF 6 DATE 9/ 1/83 TIME 8: 0

SIKORSKY AIRCRAFT DIV. - STRATFORD

	PINION	GEAR
NUMBER OF TEETH	22	75
DIAMETRAL PITCH		5.410
FACE WIDTH	1.550"	1.550"
PRESSURE ANGLE - PIN CONCAVE	20D 0M	
- PIN CONVEX	20D 0M	
SHAFT ANGLE	79D 16M	
OUTER CONE DISTANCE		7.700"
ADDENDUM	0.220"	0.084"
DEDENDUM	0.128"	0.254"
WORKING DEPTH		0.314"
WHOLE DEPTH - THEORETICAL	0.348"	0.348"
OUTSIDE DIAMETER	4.484"	13.023"
PART NUMBER		

	PINION	GEAR
PITCH APEX TO CROWN	7.370"	3.293"
PITCH ANGLE	15D 17M	63D 59M
FACE ANGLE OF BLANK	17D 10M	64D 57M
ROOT ANGLE	14D 19M	62D 6M
DEDENDUM ANGLE	0D 58M	1D 53M
SPIRAL ANGLE	35D 0M	35D 0M
HAND OF SPIRAL	LH	RH
CUTTING METHOD	FIXED SETTING	SPREAD BLADE
BACKLASH	MIN 0.004"	MAX 0.006"
DRIVING MEMBER	PIN	
DIRECTION OF ROTATION	CWE	
MOUNTING DISTANCE	MD	

GEAR TOOTH SIZES AT MIDDLE OF FACE

	SEMI-FINISH	FINISH
NORMAL CHORDAL ADDENDUM	0.081"	0.081"
NORMAL CHORDAL THICKNESS	0.172"	0.152"
MEAN WHOLE DEPTH	0.306"	0.300"

PINION TOOTH SIZES AT MIDDLE OF FACE

	SEMI-FINISH	FINISH
NORMAL CHORDAL ADDENDUM	0.198"	0.198"
NORMAL CHORDAL THICKNESS	0.286"	0.271"
MEAN WHOLE DEPTH	0.306"	0.300"

DEPTH CHECKING DATA - NO. 15 BLANK CHECKER - FINISHING

	PINION	GEAR
CHECKING DIAMETER	3.766"	12.247"
BACKING	MD - 7.370"	MD - 3.243"

RELEASED BY - Warren Gleason 42C
9-1-83

COPY, THEN GO

CUSTOMERS ORDER NO SALES ORDER NO NO OF SETS DATE

GROUND GENERATED RADIUS

	OB	IB
GEAR (.070)	.073	.073
PINION (.035)	.036	.045

Figure 10 - Gleason Gear Grinding Summary

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

GLEASON SUMMARY

GROUND GENERATED SPIRAL BEVEL SUMMARY NO. # 06342C SHEET 2 OF 6 DATE 9/ 1/83 TIME 8: 8

SIKORSKY AIRCRAFT DIV. - STRATFORD

CUTTER SPECIFICATIONS - GEAR ROUGH AND SEMI-FINISH

DIAMETER		12.000"
OUTSIDE BLADE ANGLE		18D 0M
INSIDE BLADE ANGLE		22D 0M
POINT WIDTH		0.000"
BLADE LETTER		
BLADE EDGE RADIUS		0.050"
BLADE DEPTH	STD	
TYPE OF CUTTER		
BLADE RADIUS TOLERANCE . . .	STD	
CUTTER GAGING POSITION		0.000"

GEAR ROUGH AND SEMI-FINISH - NO 26 GENERATOR

MACHINE ROOT ANGLE		62D 6M
MACHINE CENTER TO BACK . . .	MD +	0.000"
SLIDING BASE	ADV	0.001"
BLANK OFFSET		0.000"
ECCENTRIC ANGLE		53D 0M
CRADLE ANGLE		351D 10M
CRADLE TEST ROLL		30D 0M
WORK TEST ROLL		33D 22M
DECIMAL RATIO		1.1122
NC/75 RATIO GEARS		.52/66 X 72/51

GEAR SEMI-FINISHING TOOTH SIZES AT MIDDLE OF FACE

NORMAL CHORDAL ADDENDUM . .	0.081"
NORMAL CHORDAL THICKNESS . .	0.172"
MEAN WHOLE DEPTH	0.306"
BACKLASH IN RADIANS - GEAR	MIN 0.00080 MAX 0.00120

DEPTH CHECKING DATA - NO 15 BLANK CHECKER

CHECKING DIAMETER	12.247"
BACKING	MD - 3.243"

RELEASED BY - 42C

COPY, THEN GO

Figure 10 - Gleason Gear Grinding Summary (cont')

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

GROUND GENERATED SPIRAL BEVEL SUMMARY NO. # 06342C

SHEET 3 OF 6 DATE 9/ 1/03 TIME 0: 0

SIKORSKY AIRCRAFT DIV. - STRATFORD

CUTTER SPECIFICATIONS - PINION ROUGH AND SEMI-FINISH

SIDE OF TOOTH	CONCAVE - OB		CONVEX - IB
	ROUGH AND SEMI-FINISH		SEMI-FINISH
CUTTER SPECIFICATIONS			
AVERAGE DIAMETER	12.030"		
POINT DIAMETER			11.020"
OUTSIDE BLADE ANGLE	18D 0M		
INSIDE BLADE ANGLE	22D 0M		22D 0M
POINT WIDTH	0.040"		
BLADE LETTER			
BLADE EDGE RADIUS	0.025"		0.025"
BLADE DEPTH	STD		STD
TOPREM LETTER			
BLADE RADIUS TOLERANCE	STD		STD
CUTTER GAGING POSITION	0.000"		0.000"

MACHINE SETTINGS - NO 26 GENERATOR

SIDE OF TOOTH		CONCAVE - OB		CONVEX - IB
		ROUGH AND SEMI-FINISH		SEMI-FINISH
MACHINE ROOT ANGLE		14D 19M		14D 19M
MACHINE CENTER TO BACK	MD -	0.069"	MD +	0.072"
SLIDING BASE	WITH	0,019"	ADV	0.016"
BLANK OFFSET	UP	0.040"	DOWN	0.048"
ECCENTRIC ANGLE		52D 50M		53D 20M
CRADLE ANGLE		238D 39M		243D 32M
CRADLE TEST ROLL	*	20D 0M		20D 0M
WORK TEST ROLL	*	76D 30M		75D 16M
DECIMAL RATIO		1.1220		1.1039
NC/75 RATIO GEARS		52/60 X 67/45		52/64 X 72/53
ROLLER ECCENTRICITY				
ROLLER ANGLE				
ROLLER GEARS				

*DISENGAGE MODIFIED ROLL TO CHECK

PIN. SEMI-FINISHING TOOTH SIZES AT MIDDLE OF FACE

NORMAL CHORDAL ADDENDUM	0.198"
NORMAL CHORDAL THICKNESS	0.286"
MEAN WHOLE DEPTH	0.306"
BACKLASH IN RADIANS - GEAR	MIN 0.00080 MAX 0.00120

DEPTH CHECKING DATA - NO 15 BLANK CHECKER

CHECKING DIAMETER	3.766"
BACKING	MD - 7.370"

COPY, THEN GO

PROPORTIONAL CUTTING CHANGES - NO 26 GENERATOR

SIDE OF TOOTH	CONCAVE - OB		CONVEX - IB	
BIAS CHANGE - 60 MIN BIAS OUT				
MACHINE CENTER TO BACK	ADV	0.003"	WITH	0.007"
SLIDING BASE	WITH	0.023"	ADV	0.024"
ECCENTRIC ANGLE	DEC	0D 27M	INC	0D 32M
CRADLE ANGLE	DEC	0D 57M	INC	0D 50M
WORK TEST ROLL	DEC	1D 0M	INC	1D 0M
DECIMAL RATIO	DEC	0.0147	INC	0.0147
PROFILE CURVATURE CHANGE - .100" PROFILE OUT				
BLANK OFFSET	UP	0.100"	DOWN	0.10[illegible]"
ECCENTRIC ANGLE	DEC	0D 48M	INC	0D 4[illegible]M
CRADLE ANGLE	INC	0D 6M	DEC	0D 11M
WORK TEST ROLL	DEC	0D 48M	INC	0D 4[illegible]M
DECIMAL RATIO	DEC	0.0118	INC	0.011[illegible]
LENGTHWISE CURVATURE CHANGE - .100" INC IN LENGTH				
ECCENTRIC ANGLE	DEC	0D 11M	INC	0D [illegible]
CRADLE ANGLE	INC	0D 21M	DEC	0D 2[illegible]
CUTTER DIAMETER	DEC	0.100"	INC	0.10[illegible]"
SPIRAL ANGLE CHANGE - .100" OFF THE TOE				
ECCENTRIC ANGLE	DEC	0D 48M	INC	0D 46M
CRADLE ANGLE	DEC	0D 43M	INC	0D 37M

PINION CONTROL DATA

SIDE OF TOOTH	CONCAVE - OB	CONVEX - IB
PATTERN LENGTH FACTOR	0.460	0.440
DELTA AX - BIAS CHANGE	-0.100"	0.100"
DELTA EP - PROFILE FACTOR	0.000"	0.000"
KP	0.000	0.000
DELTA E - THIRD ORDER	0.000"	0.000"
DELTA 2C	0.000	0.000
DELTA 6CX	0.000	0.000

Figure 10 - Gleason Gear Grinding Summary (cont')

GLEASON SUMMARY

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

GROUND GENERATED SPIRAL BEVEL SUMMARY NO. # 06342C SHEET 4 OF 6 DATE 9/ 1/83 TIME 8: 0

SIKORSKY AIRCRAFT DIV. - STRATFORD

GRINDING WHEEL SPECIFICATIONS - GEAR

SIDE OF TOOTH		BOTH
DIAMETER		12.000"
OUTSIDE WHEEL PRESSURE ANGLE		18D 0M
INSIDE WHEEL PRESSURE ANGLE		22D 0M
POINT WIDTH		0.110"
WHEEL EDGE RADIUS		0.070"

MACHINE SETTINGS - NO 27 GRINDER

MACHINE ROOT ANGLE		62D 6M
MACHINE CENTER TO BACK . . .	MD +	0.000"
SLIDING BASE	ADV	0.001"
BLANK OFFSET		0.000"
CAM SETTING		2.074"
ECCENTRIC ANGLE		44D 14M
CRADLE ANGLE		76D 47M
CAM GUIDE ANGLE		0D 0M
FEED CAM SETTING		0D 0M
GENERATING CAM NUMBER . . .		46380128
INDEX INTERVAL		11
INDEX GEARS		34/85 X 33/90

GRINDER DRESSER SETTINGS - GEAR

DRESSER BLOCK ANGLE		40D 0M
OUTSIDE PRESSURE ANGLE . . .		18D 0M
SIDE DRESSER RADIAL		6.120"
OUTSIDE DRESSER ARM		45801921
OUTSIDE DIAMOND NIB HOLDER .		45822580
OUTSIDE DIAMOND NIB EXTENSION		45822620
OUTSIDE DIAMOND SETTING . .		0.020"
INSIDE DRESSER ARM		45801911
INSIDE DIAMOND NIB HOLDER .		45822570
INSIDE DIAMOND NIB EXTENSION		45822620
INSIDE DIAMOND SETTING . . .	WITH	0.237"
SIDE DRESSER AXIAL		0.000"
SIDE DRESSER OFFSET		0.000"
RADIUS CAM NUMBER		45880203
SWING ANGLE		18D 0M
END DIAMOND NIB HOLDER . . .		45822580
END DIAMOND NIB EXTENSION .		45822620
END DIAMOND SETTING	WITH	0.070"
END DRESSER RADIAL		6.013"

GEAR FINISHING TOOTH SIZES AT MIDDLE OF FACE

NORMAL CHORDAL ADDENDUM . .	0.081"
NORMAL CHORDAL THICKNESS . .	0.152"
MEAN WHOLE DEPTH	0.300"
BACKLASH IN RADIANS - GEAR MIN 0.00080 MAX	0.00120

DEPTH CHECKING DATA - NO 15 BLANK CHECKER

CHECKING DIAMETER	12.247"
BACKING . . . . MD -	3.243"

RELEASED BY - 42C

COPY, THEN GO

Figure 10 - Gleason Gear Grinding Summary (cont')

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

GLEASON SUMMARY

GROUND GENERATED SPIRAL BEVEL SUMMARY NO. # 86342C SHEET 5 OF 6 DATE 0/ 1/83 TIME 0: 0

SIKORSKY AIRCRAFT DIV. - STRATFORD

GRINDING WHEEL SPECIFICATIONS - PINION

SIDE OF TOOTH	CONCAVE - OB	CONVEX - IB
POINT DIAMETER	12.070"	11.920"
OUTSIDE WHEEL PRESSURE ANGLE	18D 0M	18D 0M
INSIDE WHEEL PRESSURE ANGLE	22D 0M	22D 0M
POINT WIDTH	0.040"	0.040"
WHEEL EDGE RADIUS	0.035"	0.035"

MACHINE SETTINGS - NO 27 GRINDER

MACHINE ROOT ANGLE		14D 19M		14D 19M
MACHINE CENTER TO BACK . . .	MD -	0.069"	MD +	0.072"
SLIDING BASE	WITH	0.019"	ADV	0.016"
BLANK OFFSET	UP	0.040"	DOWN	0.040"
CAM SETTING		3.969"		4.023"
ECCENTRIC ANGLE		44D 6M		44D 30M
CRADLE ANGLE		324D 17M		320D 7M
CAM GUIDE ANGLE		0D 0M		0D 0M
FEED CAM SETTING		0D 0M		0D 0M
GENERATING CAM NUMBER . . .		46300123		46300123
INDEX INTERVAL		13		13
INDEX GEARS		56/70 X 65/80		56/70 X 65/80

GRINDER DRESSER SETTINGS - PINION

DRESSER BLOCK ANGLE		40D 0M		40D 0M
OUTSIDE PRESSURE ANGLE . . .		18D 3M		17D 56M
SIDE DRESSER RADIAL		6.071"		5.870"
OUTSIDE DRESSER ARM		45801921		45801921
OUTSIDE DIAMOND NIB HOLDER .		45822580		45822580
OUTSIDE DIAMOND NIB EXTENSION		45822620		45822620
OUTSIDE DIAMOND SETTING . .		0.000"	WITH	0.156"
INSIDE DRESSER ARM		45801911		45801911
INSIDE DIAMOND NIB HOLDER .		45822580		45822580
INSIDE DIAMOND NIB EXTENSION		45822620		45822620
INSIDE DIAMOND SETTING . . .	WITH	0.155"		0.000"
SIDE DRESSER AXIAL	OUT	0.026"	OUT	0.031"
SIDE DRESSER OFFSET	UP	0.500"	DOWN	0.500"
RADIUS CAM NUMBER		45800204		45800204
SWING ANGLE		18D 0M		18D 0M
END DIAMOND NIB HOLDER . . .		45822580		45822580
END DIAMOND NIB EXTENSION .		45822620		45822620
END DIAMOND SETTING	WITH	0.035"	WITH	0.035"
END DRESSER RADIAL		6.010"		5.875"

COPY, THEN GO

PROPORTIONAL GRINDING CHANGES - NO 27 GRINDER

SIDE OF TOOTH	CONCAVE - OB		CONVEX - IB	
BIAS CHANGE - .100" BIAS OUT				
MACHINE CENTER TO BACK . . .	ADV	0.075"	WITH	0.074"
SLIDING BASE	WITH	0.019"	ADV	0.018"
BLANK OFFSET	DOWN	0.100"	UP	0.100"
ECCENTRIC ANGLE	INC	0D 21M	DEC	0D 18M
CRADLE ANGLE	DEC	0D 56M	INC	0D 58M
PROFILE CURVATURE - 1 DEG PROFILE OUT				
CAM SETTING	DEC	0.000"	DEC	0.000"
CAM GUIDE ANGLE	CW	1D 0M	CCW	1D 0M
LENGTHWISE CURVATURE CHANGE - .100" INC IN LENGTH				
ECCENTRIC ANGLE	DEC	0D 8M	INC	0D 7M
CRADLE ANGLE	INC	0D 22M	DEC	0D 23M
WHEEL DIAMETER	DEC	0.100"	INC	0.100"
SPIRAL ANGLE CHANGE - .100" OFF THE TOE				
ECCENTRIC ANGLE	DEC	0D 39M	INC	0D 37M
CRADLE ANGLE	DEC	0D 30M	INC	0D 33M
CAM POSITION CHANGE - .050" INC. IN CAM SETTING				
MACHINE CENTER TO BACK . . .	ADV	0.050"	ADV	0.057"
SLIDING BASE	WITH	0.012"	WITH	0.014"
BLANK OFFSET	UP	0.077"	UP	0.074"
ECCENTRIC ANGLE	DEC	0D 42M	DEC	0D 43M
CRADLE ANGLE	DEC	0D 21M	DEC	0D 21M
CAM SETTING	INC	0.050"	INC	0.050"

PINION FINISHING TOOTH SIZES AT MIDDLE OF FACE

NORMAL CHORDAL ADDENDUM . .	0.108"
NORMAL CHORDAL THICKNESS . .	0.271"
MEAN WHOLE DEPTH	0.300"
BACKLASH IN RADIANS - GEAR MIN 0.00000 MAX	0.00120

DEPTH CHECKING DATA - NO 15 BLANK CHECKER

CHECKING DIAMETER	9.766"
BACKING . . . . MD -	7.370"

V/H CHECK SOFT GEAR SOFT PINION
CONCAVE TOE HEEL TOTAL CONVEX TOE HEEL TOTAL
V V
H H

UNDEVELOPED SETTINGS - UNCONFIRMED FOR PRODUCTION

Figure 10 - Gleason Gear Grinding Summary (cont')

GLEASON SUMMARY

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

SPIRAL BEVEL GEAR DIMENSIONS   NO. # 06342C   FORM M   DATE 8/30/83   TIME 14:50

SIKORSKY AIRCRAFT DIV. - STRATFORD

	PINION	GEAR
NUMBER OF TEETH	22	76
PART NUMBER		
DIAMETRAL PITCH		5.419
FACE WIDTH	1.550"	1.550"
PRESSURE ANGLE	20D 0M	
SHAFT ANGLE	79D 16M	
TRANSVERSE CONTACT RATIO		1.248
FACE CONTACT RATIO		2.000
MODIFIED CONTACT RATIO		2.434
OUTER CONE DISTANCE		7.700"
MEAN CONE DISTANCE		6.925"
PITCH DIAMETER	4.060"	13.840"
CIRCULAR PITCH	0.580"	
WORKING DEPTH	0.314"	
WHOLE DEPTH	0.348"	0.348"
CLEARANCE	0.034"	0.034"
ADDENDUM	0.220"	0.094"
DEDENDUM	0.128"	0.254"
OUTSIDE DIAMETER	4.484"	13.923"
FACE ANGLE JUNCTION DIAMETER		
THEORETICAL CUTTER RADIUS	6.555"	
CUTTER RADIUS	6.000"	
CALC. GEAR FINISH. PT. WIDTH		0.110"
GEAR FINISHING POINT WIDTH		0.110"
ROUGHING POINT WIDTH	0.040"	0.080"
OUTER SLOT WIDTH	0.062"	0.110"
MEAN SLOT WIDTH	0.071"	0.110"
INNER SLOT WIDTH	0.071"	0.110"
FINISHING CUTTER BLADE POINT	0.040"	0.065"
STOCK ALLOWANCE	0.022"	0.020"
MAX. RADIUS CUTTER BLADES	0.040"	0.074"
MAX. RADIUS-MUTILATION	0.054"	0.093"
MAX. RADIUS-INTERFERENCE	0.041"	0.065"
CUTTER EDGE RADIUS	0.035"	0.070"
CALC. CUTTER NUMBER	3	6
MAX. NO. BLADES IN CUTTER		17.614
CUTTER BLADES REQUIRED	STD DEPTH	STD DEPTH
GEAR ANGULAR FACE - CONCAVE		17D 34M
GEAR ANGULAR FACE - CONVEX		18D 42M
GEAR ANGULAR FACE - TOTAL		20D 26M

COPY, THEN GO

		PINION		GEAR
PITCH APEX TO CROWN		7.370"		3.203"
FACE ANG JUNCT TO PITCH APEX				
MEAN CIRCULAR THICKNESS		0.330"		0.104"
OUTER NORMAL TOP LAND		0.103"		0.080"
MEAN NORMAL TOP LAND		0.105"		0.091"
INNER NORMAL TOP LAND		0.108"		0.089"
PITCH ANGLE		15D 17M		63D 59M
FACE ANGLE OF BLANK		17D 10M		64D 57M
INNER FACE ANGLE OF BLANK				
ROOT ANGLE		14D 10M		62D 6M
DEDENDUM ANGLE		0D 58M		1D 53M
OUTER SPIRAL ANGLE				30D 41M
MEAN SPIRAL ANGLE				35D 0M
INNER SPIRAL ANGLE				30D 34M
HAND OF SPIRAL	LH		RH	
DRIVING MEMBER	PIN			
DIRECTION OF ROTATION-DRIVER	CWE			
OUTER NORMAL BACKLASH	MIN	0.004"	MAX	0.006"
DEPTHWISE TOOTH TAPER	GIVN			
GEAR TYPE				GENERATED
FACE IN PERCENT OF CONE DIST				20.120
DEPTH FACTOR - K				
ADDENDUM FACTOR - C1				
GEOMETRY FACTOR-STRENGTH-J		0.3277		0.3772
STRENGTH FACTOR-Q		3.44515		0.87783
EDGE RADIUS USED IN STRENGTH		0.035"		0.070"
CUTTER RADIUS FACTOR - KX		1.038		
FACTOR	MN	0.7206		
STRENGTH BALANCE DESIRED	GIVN			
STRENGTH BALANCE OBTAINED	GIVN			0.116
GEOMETRY FACTOR-DURABILITY-I		0.1376		
DURABILITY FACTOR-Z		2133.63		1155.58
GEOMETRY FACTOR-SCORING-G		0.003132		
SCORING FACTOR - X		0.2244		
ROOT LINE FACE WIDTH		1.550"		1.550"
PROFILE SLIDING FACTOR		0.00301		0.00630
RATIO OF INVOLUTE/MEAN CONE		1.220		
AXIAL FACTOR-DRIVER CW	OUT	0.434	OUT	0.015
AXIAL FACTOR-DRIVER CCW	IN	0.306	OUT	0.114
SEPARATING FACTOR-DRIVER CW	SEP	0.134	SEP	0.132
SEPARATING FACTOR-DRIVER CCW	SEP	0.336	ATT	0.070
DUPLEX SUM OF DEDENDUM ANG		2D 27M		
ROUGHING RADIAL		6.025"		
INPUT DATA	KTT GIVN			
INPUT DATA	CUTM			

Figure 10 - Gleason Gear Grinding Summary (cont')

GLEASON SUMMARY

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

GROUND BEVEL SUMMARY NO. 0 342C SHEET 6 OF 6 DATE 8/31/88 TIME 16:10

SIKORSKY AIRCRAFT DIV. - STRATFORD

NO. 463 GRINDER
ADDITIONAL MACHINE EQUIPMENT - GEAR

MATERIAL TYPE	STEEL
WHEEL SURFACE SPEED-SFM* . .	4000.
APPROX. SPINDLE R.P.M.* . .	1273.
WHEEL BORE SIZE	0.000"
WHEEL INSIDE DIAMETER . . .	11.250"
WHEEL OUTSIDE DIAMETER . . .	12.625"
WHEEL GRADING OR EQUIVALENT	32A54-J8VBE
WHEEL ADAPTER	46300202
WHEEL GUARD	46080505
WHEEL ROTATION	TOE-HEEL
WHEEL FEED CAM	45004920
VARIABLE STOP DRUM	45000500
WHEEL FEED FOR DRESSING . .	0.003"
MACHINE FEED SEC./TOOTH . .	3.0

GRINDING SEQUENCE	ROUGHING	FINISHING
SIDE DRESSER ARMS	8	16
END DRESSER ARM	8	8
DRESS NOS.	9, 6, 3	
START ON NO.	0	

*REFER TO MACHINE CHART FOR PULLEY NUMBERS AND BELT LENGTHS.

RELEASED BY 42C

PRINTER OUTPUT? YES OR NO

NO. 469 GRINDER
ADDITIONAL MACHINE EQUIPMENT - PINION

MATERIAL TYPE	STEEL	STEEL
WHEEL SURFACE SPEED-SFM* . .	4000.	4000.
APPROX. SPINDLE R.P.M.* . .	1266.	1282.
WHEEL BORE SIZE	0.000"	0.000"
WHEEL INSIDE DIAMETER . . .	11.250"	11.250"
WHEEL OUTSIDE DIAMETER . . .	12.625"	12.500"
WHEEL GRADING OR EQUIVALENT	32A80-J8VBE	32A80-J8VDE
WHEEL ADAPTER	46300202	46300202
WHEEL GUARD	46080505	46080506
WHEEL ROTATION	HEEL-TOE	HEEL-TOE
WHEEL FEED CAM	45004920	45004920
VARIABLE STOP DRUM	45000500	45000500
WHEEL FEED FOR DRESSING . .	0.003"	0.003"
MACHINE FEED SEC./TOOTH . .	3.0	3.0

GRINDING SEQUENCE	ROUGHING	FINISHING
SIDE DRESSER ARMS	8	16
END DRESSER ARM	8	8
DRESS NOS.	9, 6, 3	9, 6, 3
START ON NO.	9	9

Figure 10 - Gleason Gear Grinding Summary (cont')

GLEASON SUMMARY

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

SIKORSKY AIRCRAFT DIV. - STRATFORD

SUMMARY NO. # 06342C
RATIO 22 X 75 DATE 8/31/83

GEAR	CONVEX	CONCAVE
PIN BLADE ANG.	18.00	22.00
GEAR BLADE ANG	22.00	18.00
POINT DIAMETER	12.070	11.920
CONT LGTH FACT	0.46	0.44
DELTA AX . . .	-0.100	0.100
DELTA E. . . .	0.000	0.000
KP	0.000	0.000
DELTA EM . . .	0.000	0.000
DELTA 6CX. . .	0.000	0.000
DELTA 2C . . .	0.000	0.000
DELTA E-OR . .	-0.500	0.500

GEAR	CONVEX	CONCAVE
TOE POSITION	0.25	0.25
HEEL POSITION	0.17	0.17

IN*1000		MEAN	TOE	HEEL	TOTAL
CX	E(V)	-4	21	-27	47
	P(H)	3	-19	24	42
CV	E(V)	-2	-29	36	65
	P(H)	-2	20	-37	57

INCREMNT: MOTION 40, CONTACT 0.25
NOTE: A001 SPEC ANALYSIS FILE

RERUN? TYPE NO, DP, VH, FE, XX, OR END

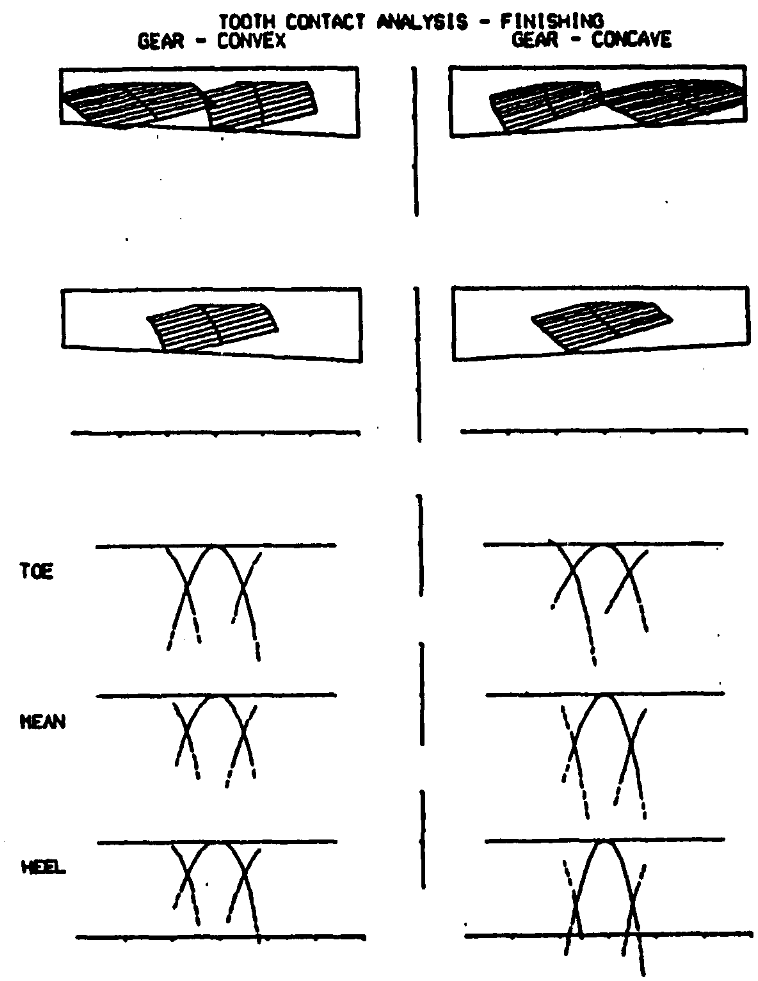


Figure 10 - Gleason Gear Grinding Summary (cont')

on a reference diameter to establish the location of the Z axis of the gear in relation to the machine axis.

The reference coordinate system for the nominal data for the gear is then located along the gear axis, generally at the pitch cone apex or mounting shoulder. In order to determine the angle of rotation of the gear's polar coordinate system relative to the machine's coordinate system, a known point on the tooth flank is contacted and the deviation of this point from nominal set to zero.

The tooth flanks are measured in CNC mode. Nominal points on the network are loaded from the disc into core memory and transformed into machine coordinates. The computer keeps track of the momentary position of the probe and determines the path to the next point. The measured deviations from the nominal surface are determined along the projected surface normals.

Current G-AGE™ Corrective Process

One of the prime requirements identified at the outset for an improved spiral bevel gear inspection system was that if the profile deviations of a production gear, as measured on the coordinate measuring machine, are beyond acceptable limits; these deviations must be interpretable in terms of specific delta changes to the grinding machine settings used to produce that gear. The procedure is essentially the inverse of the mathematical simulation process described earlier and is accomplished by the Gleason Works G-AGE™ software package described below.

After a spiral bevel gear set has been approved for operation in a particular gearbox the final grinding machine settings are used to calculate the theoretical surface coordinates and nominal values. This information is down-loaded, through a modem, and stored on a data disc . Along with this theoretical surface data, a corrective matrix is also generated and stored on the same data disc. The corrective matrix can be considered as a surface sensitivity matrix. For example, changes that affect the pressure angle and spiral angle of the tooth surface are defined. The sensitivity of the surface to these changes is calculated and stored in the corrective matrix. Changes are defined for each Gleason cutting or grinding machine. When the tooth surfaces of the individual gears are measured and compared to the nominal value matrix (either calculated theoretical surface points or measured surface points from a master gear), a matrix of error data is computed and stored. The error data is then multiplied by the corrective matrix and the first-order corrective settings for the grinding machine are calculated and printed out.

ENHANCEMENT OF THE AUTOMATED INSPECTION PROCESS

To further improve the spiral bevel gear inspection process described above, Sikorsky performed the following tasks to demonstrate and validate the theoretical corrective matrix for both first and second-order machine change capability. Once validated, the improved correction matrix can then be used by the coordinate measuring machine to automatically compute first and second-order machine setting changes in a production mode. The benefits of this enhancement in terms of a further reduction in fabrication time and cost are evaluated by the economic analysis of Task 5.

Task 1 - Selection of Components

The specific components or gear sets that were used to verify the improvements in the gear inspection process, realized by the automation of the second-order change calculations, were selected from Sikorsky's BLACK HAWK/SEAHAWK power transmissions.

The BLACK HAWK shown in Figure 11 is the Army's advanced twin engine tactical transport helicopter manufactured by Sikorsky Aircraft to perform the missions of assault, resupply, medical evacuation, command and control, and tactical positioning of reserves. Two GE-T701C turboshaft engines deliver 1,700 horsepower each to the BLACK HAWK drive system. The main transmission, shown in Figure 12, consists of a main module, two interchangeable input modules, and two interchangeable accessory modules. The main transmission transmits 3,400 maximum continuous horsepower with an input speed of 20,900 RPM.

The Navy derivative of the BLACK HAWK is the SH-60B SEAHAWK. The drive trains are identical except for the fact that the Navy aircraft has rotor- braking and tail-folding capability.

The two bevel gear meshes originally selected to verify the enhancement of the spiral bevel gear inspection process were:

(1) Main Module Pinion and Gear Set
P/N 70351-38104 and 70351-38114

(2) Input Module Pinion and Gear Set
P/N 70351-08205 and 70351-08221

The input module bevel gear mesh has a speed reduction ratio of 3.64 and rotates at the engine input speed of 20900 RPM. It transmits 1700 horsepower each on a continuous basis and has a single-engine capability of 1900 horsepower.

The main module bevel gear mesh has a reduction ratio of 4.76 with an input speed of 5748 RPM. It is the second stage mesh and delivers the same horsepower as the input mesh.

These two selected spiral bevel gear sets are part of the Improved Durability Gearbox (IDGB) design used in both the BLACK HAWK and

Figure 11 - BLACK HAWK Utility Helicopter

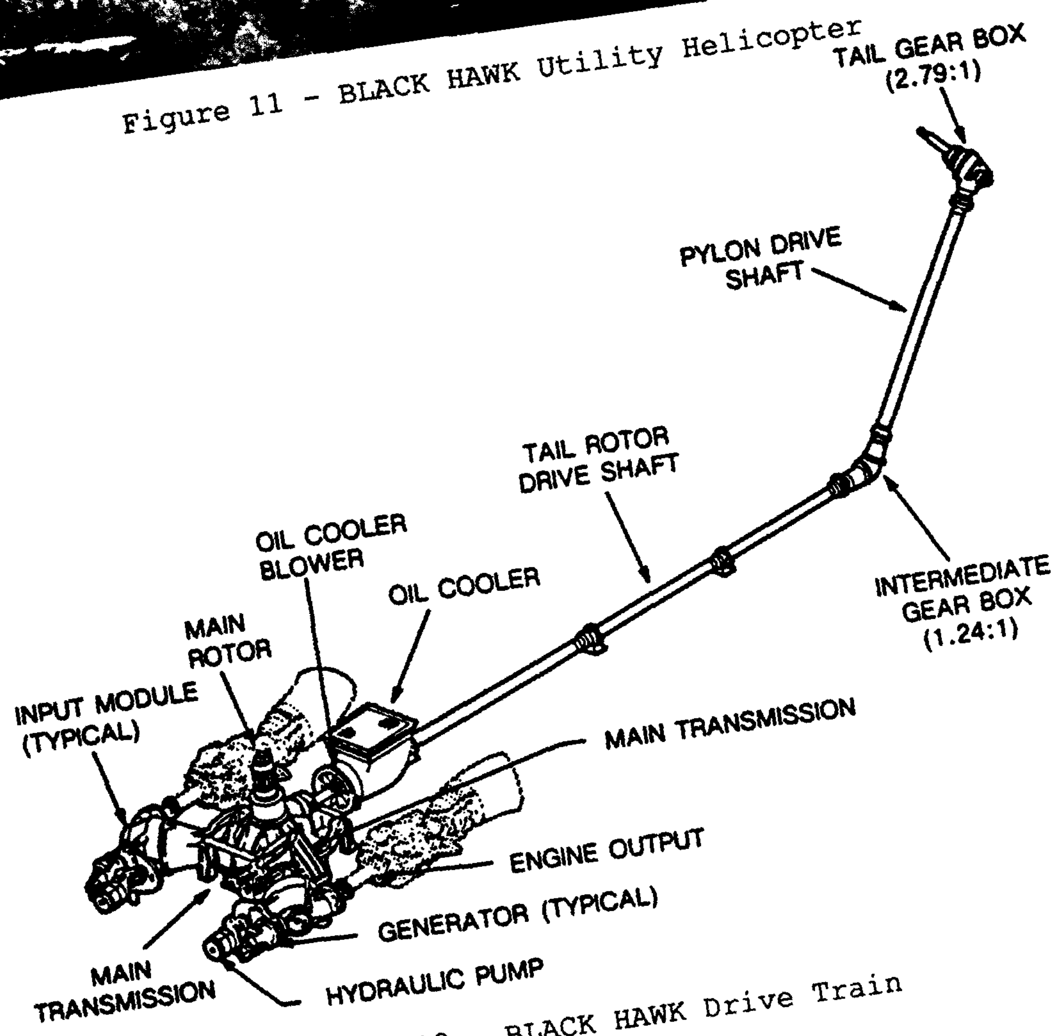


Figure 12 - BLACK HAWK Drive Train

SEAHAWK transmissions and are shown highlighted in Figure 13 and close up in Figure 14.

Task 2 - Establishment of Baseline Values

In order to establish a baseline process and quantify the advantages of an enhanced spiral bevel gear inspection system, which includes the automatic calculation of second-order corrections, the selected gear sets were measured on the Zeiss three-coordinate measuring machine, using the Zeiss/Gleason software package featuring the automatic calculation of corrections for first-order changes only. These measurements were made during production runs on these selected gears and, therefore, did not require the manufacture of special test-gear sets. Typical outputs from these measurements are shown in Figures 15 and 16. Figure 15 shows the bevel gear, P/N 70351-38114, with a second-order bias-out condition. Figure 16 shows the indicated first-order correction for this gear which, it should be noted, does not correct this second-order variance. The bias correction, which involves a cam guide angle change, was hand calculated.

The man-hours expended for each of the required machining, inspection, remachining steps were documented as well as the additional hours required for the manual calculations and iterations of the second order changes, where necessary. The results of these time studies are shown in Table 1.

Task 3 - Establishment of Second-Order Corrections

Selected Gear Set No. 1.

The first step in this task was to establish the basic dimension sheets and summary files for each of the selected components. This was accomplished using the Sikorsky Tektronix computer terminal which is on-line with the Gleason Works mainframe computer. The following Gleason programs were run for each gear set.

- T2000 — The Gear Dimension Sheet
- T2000 — The TCA and Summary Sheet which includes all of the machine settings and related gear blank dimensions.
- A 622 — The Gear Grinding Sequence Program
- T606 — This Program Converts Grinder Settings to Basic Settings
- T801Z0 — The Tooth Form Generator and Correction Package. This program generates the theoretical XYZ surface coordinate points and the corrective matrix including now first and second order changes.

A Special Analysis File (SAF) was thereby established, for each selected gear set, which included the final machine settings and the

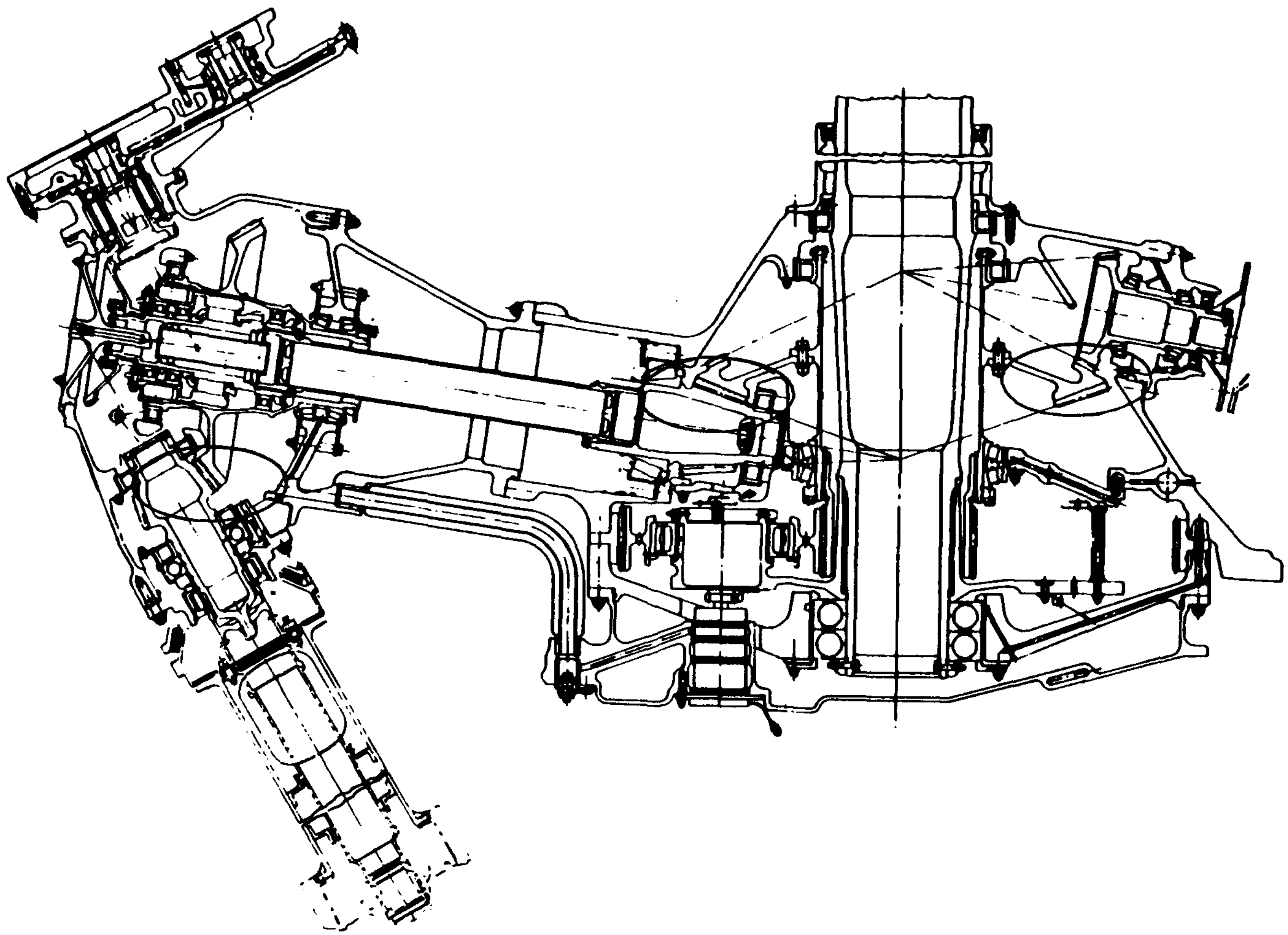
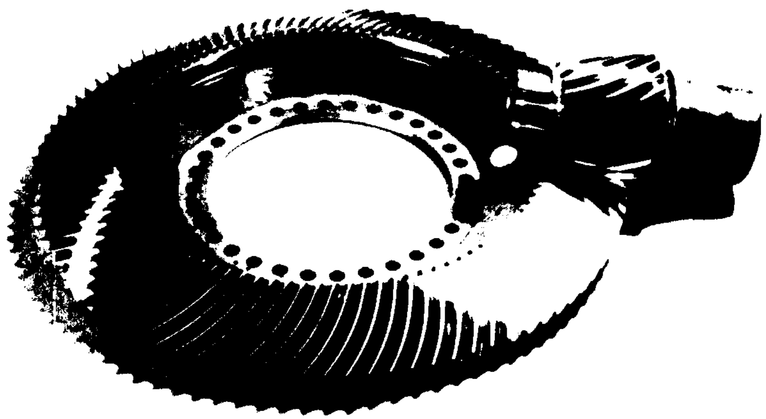
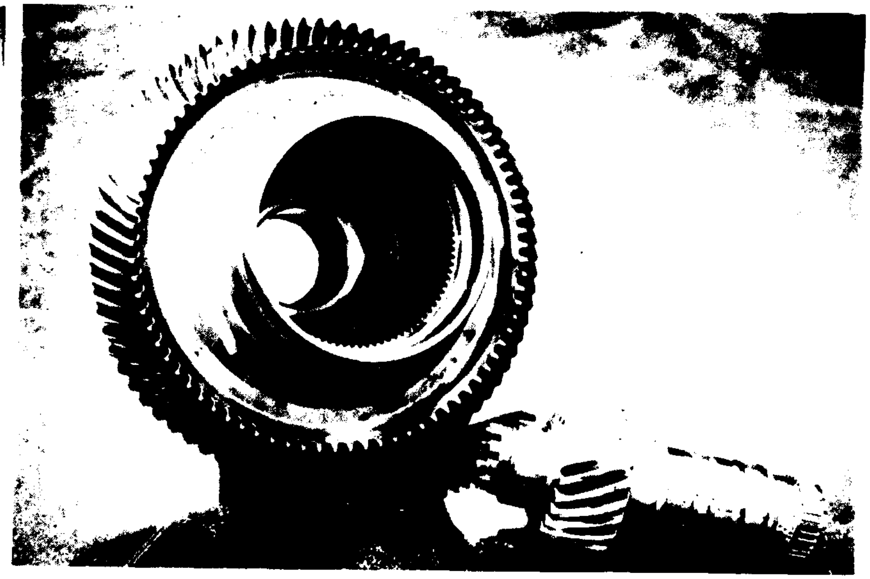


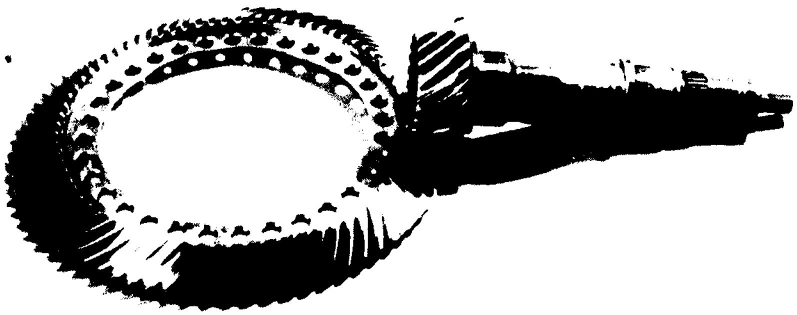
Figure 13 - Cross Section of BLACK HAWK Main Gearbox



Selected Set No. 1



Selected Set No. 2



Alternate Gear Set

Figure 14 - Selected Gear Sets

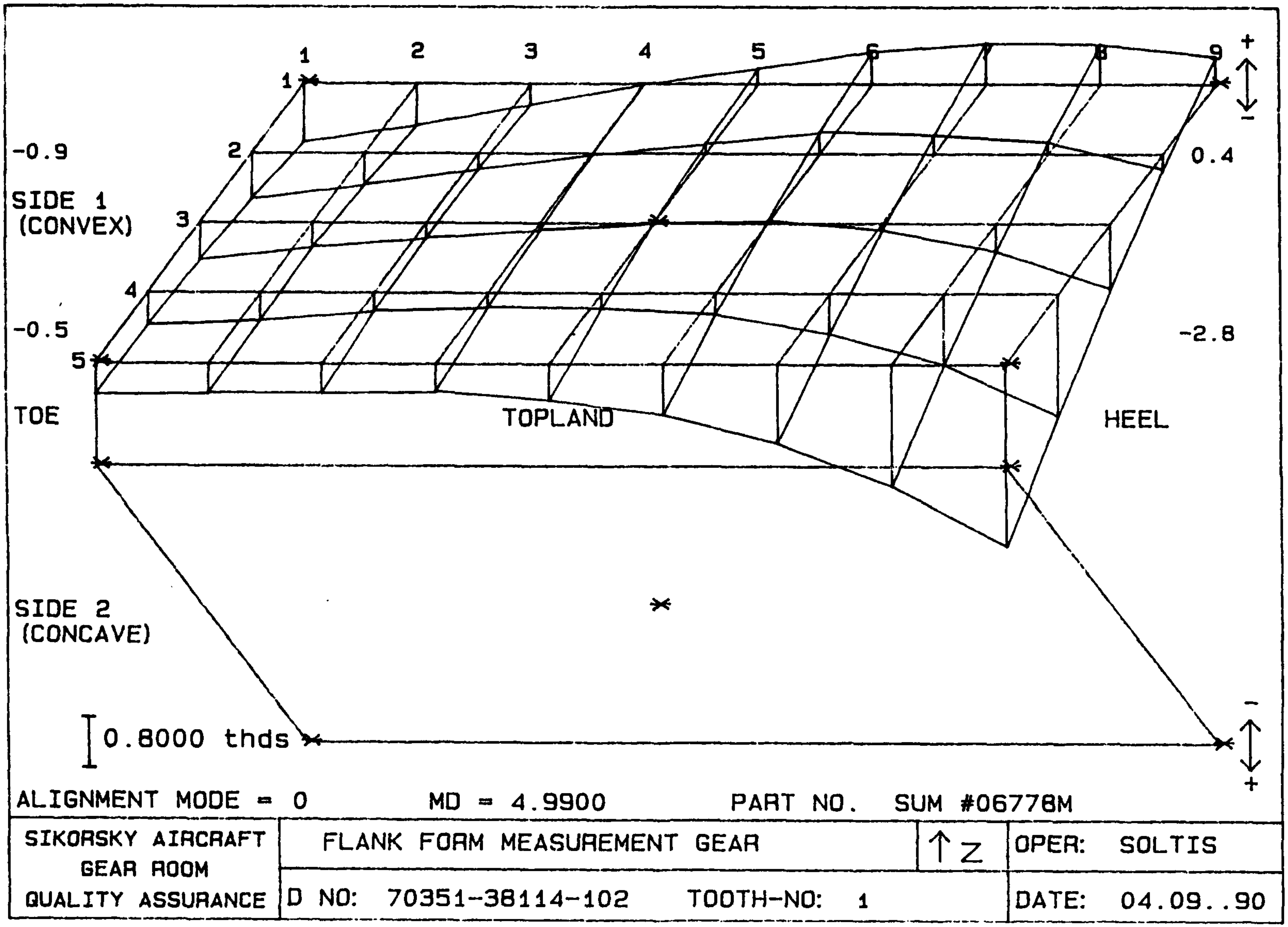


Figure 15 - Baseline Plot of Gear Member-Set No. 1

```
    STORAGE    1.02

463 MACHINE SETTING CHANGES        1st ORDER   GEAR     CONVEX
FILE    1.02

          ECCENTRIC ANGLE ............          0 min
          CRADLE ANGLE ...............          0 min
          SLIDING BASE ...........WITH    0.0000 inches
          MACHINE ROOT ANGLE..........          0 min
          DRESSER O.B.ANGLE ..........         19 min
          CAM GUIDE ANGLE ..........CW          0 min
          CAM SETTING ................      0.000 inches
             AVERAGE ERRORS        SIDE       1         2
          PRESSURE ANGLE .............      13.78     0.00 min
          SPIRAL ANGLE ...............       0.22     0.00 min
          WARP FACTOR ................       1.52     0.00
          SUM MEAS ERRORS SQ        orig     0.000025723
                                 1st ord     0.000016358
```

Figure 16 - Baseline First Order Setting Changes

TABLE - 1. SAVINGS ANALYSIS

Savings in Hours per Lot (Set-Up)

	Hand Calculated 1st & 2nd Order		#463 Grinder 1st & 2nd Order		Total Savings in Hours
	Gear	Pinion	Gear	Pinion	
70351-38151 Pinion		54.6		19.8	34.8
70351-38167 Gear	50.7		24.2		26.5
70351-38104 Pinion		65.2		19.7	45.5
70351-38114 Gear	64.6		34.1		30.5
Totals	115.3	119.8	58.3	39.5	137.3

theoretical XYZ coordinates of the tooth profile. The corresponding corrective matrix was also established for each mesh.

The T015 grand master gear and pinion for the first selected gear set were then set up in the Zeiss™ machine and measured. The flank form on both the concave and convex sides of both master pinion and gear were mapped at 45 grid points covering the active surfaces of the tooth. The deviations from the theoretical nominal surface were obtained and the corrective settings, for both first and second-order changes, generated. The results demonstrated a measurable variation between the measured tooth surface and the theoretical nominal XYZ values derived from the final machine settings. Figures 17 and 18 show the Zeiss/Gleason measurement results for the T015 Grand master gears, P/N 70351-38114, and pinion, P/N 70351-38104, based on the SAF, adjusted to the same set-up values used to grind the same masters on the Gleason #463 grinder. This variance indicates that the theoretical model in the Gleason mainframe computer did not duplicate the form ground on the #463 grinder and an adjustment of the theoretical points in the SAF would be necessary.

Using the Tektronik terminal and the Gleason T606 program, new XYZ theoretical points and a new corrective matrix were generated and down-loaded to the HP computer on the Zeiss™ machine as before. This process was repeated until it was confirmed that the corrected theoretical data adequately duplicated the measured tooth profile. A sample gear, ground on the #463 Gleason Grinder, was then measured on the Zeiss using the new theoretical data. The final result is shown in Figure 19. The correction data indicated some machine changes which would be difficult to make on the grinder due to the inherent sensitivity of the manual settings on this machine. Two or more iterations generally would be required to make the gear acceptable. The Gleason #463 and 137 grinders consist of machine settings which use verniers, dials, and slides which are all manually adjusted. Backlash in the screws must be considered as a source of error. This inability to make accurate adjustments make it difficult to obtain correct settings the first time. For these reasons, it was expected, and later verified, that the correction program would work much better on the new CNC Phoenix Grinder.

The Phoenix 400PG, recently installed at Sikorsky and shown in Figure 20, is a full 6-axis CNC machine tool specifically designed to more efficiently grind generated spiral bevel and hypoid gears. The machine uses a new concept whereby all necessary relative motions are provided by six CNC axes. Three axes of motion are rotational including the cutter spindle, work spindle, and the swinging base. The X-horizontal cutter axis, Y-vertical cutter axis, and Z-sliding base are linear axes of motion. Each axis is controlled by independent AC servo drives and precision ballscrews. Incremental rotary encoders indicate the position of the rotary axes and incremental linear encoders mounted directly to the moving slides provide position feedback for the linear axes of motion.

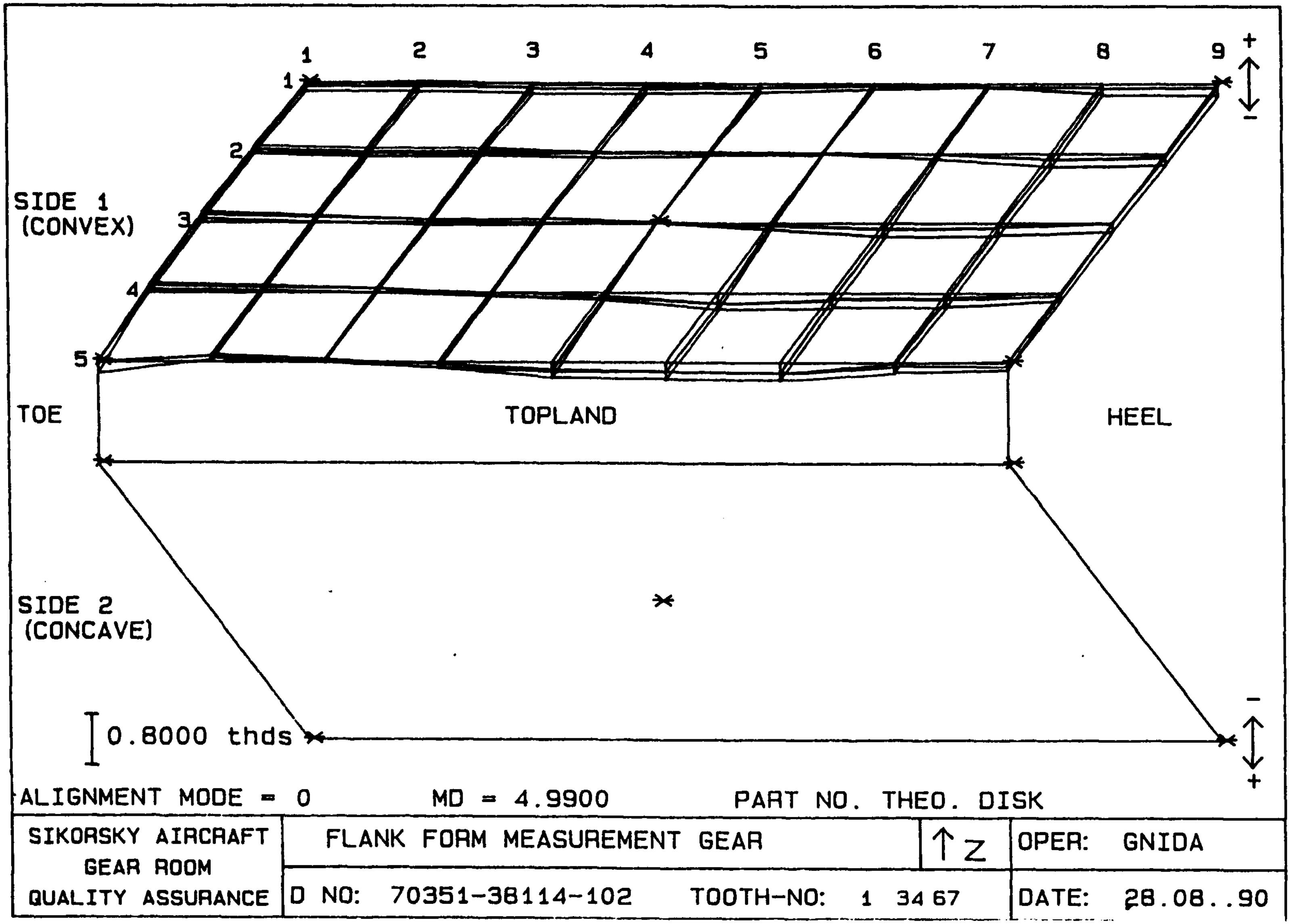


Figure 17 - Zeiss/Gleason Measurement Results - Gear Set No. 1

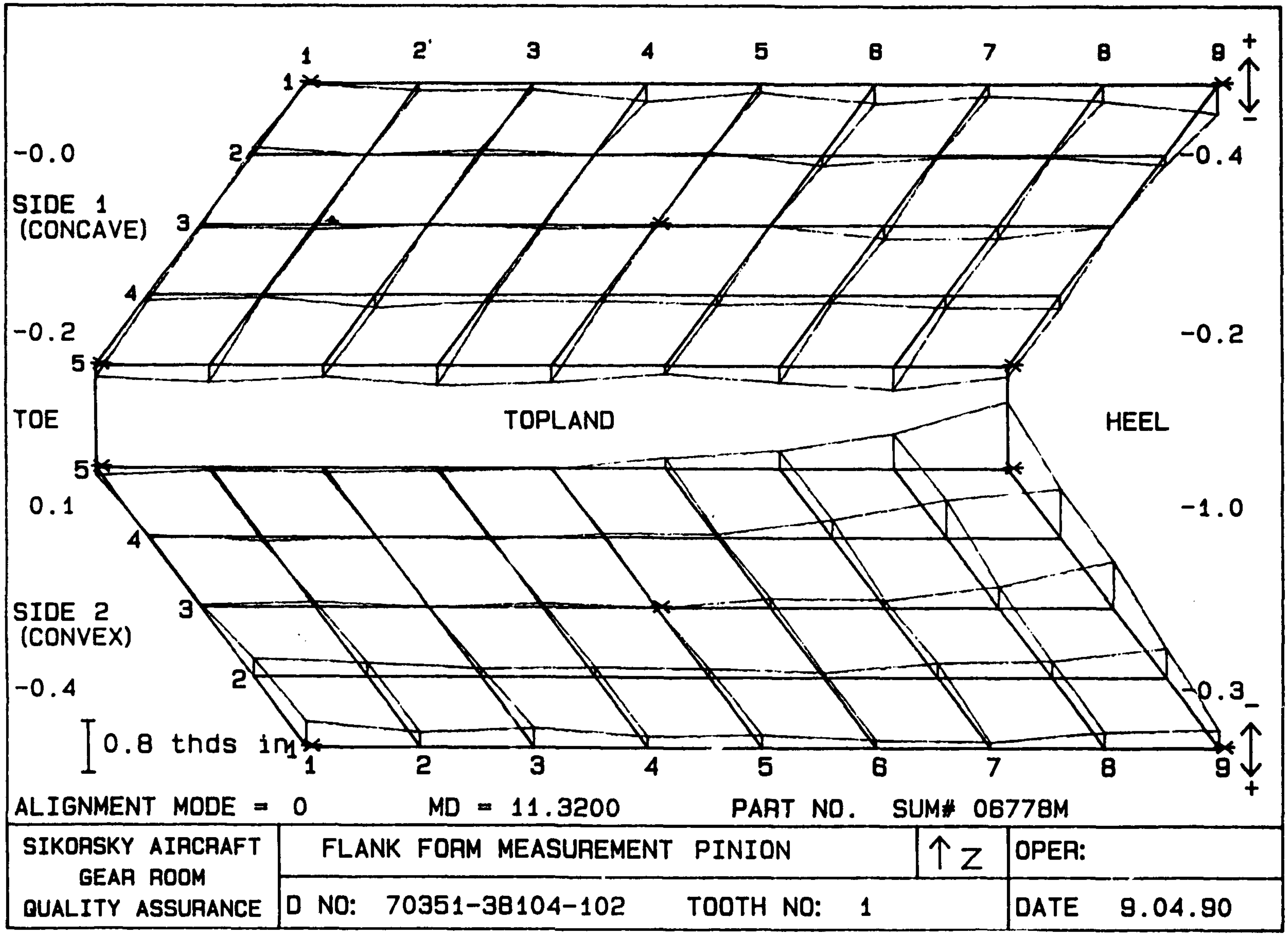


Figure 18 - Zeiss/Gleason Measurement Results - Pinion Set No. 1

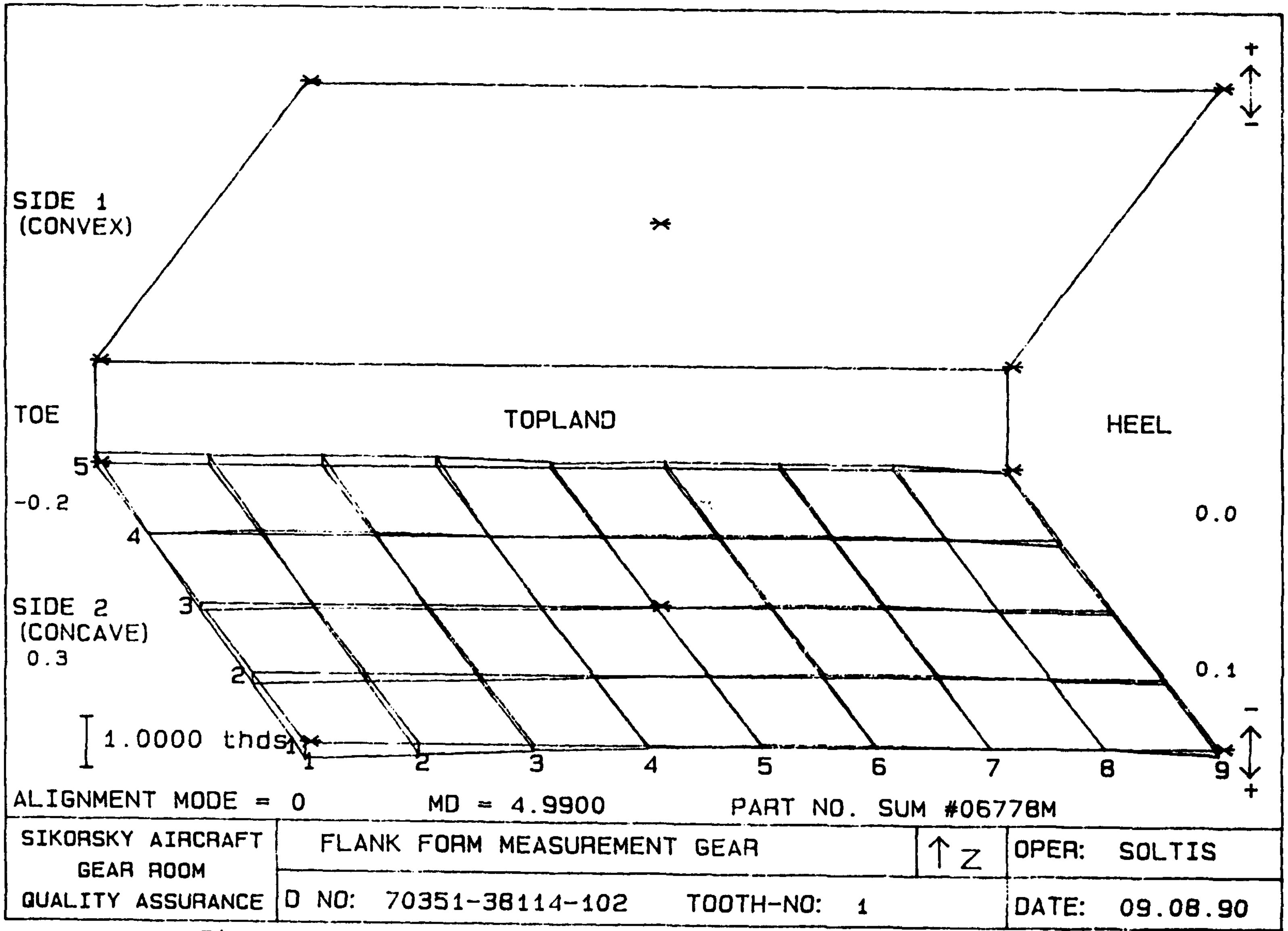


Figure 19 - Measurement Results - Gear Set No. 1 Corrected

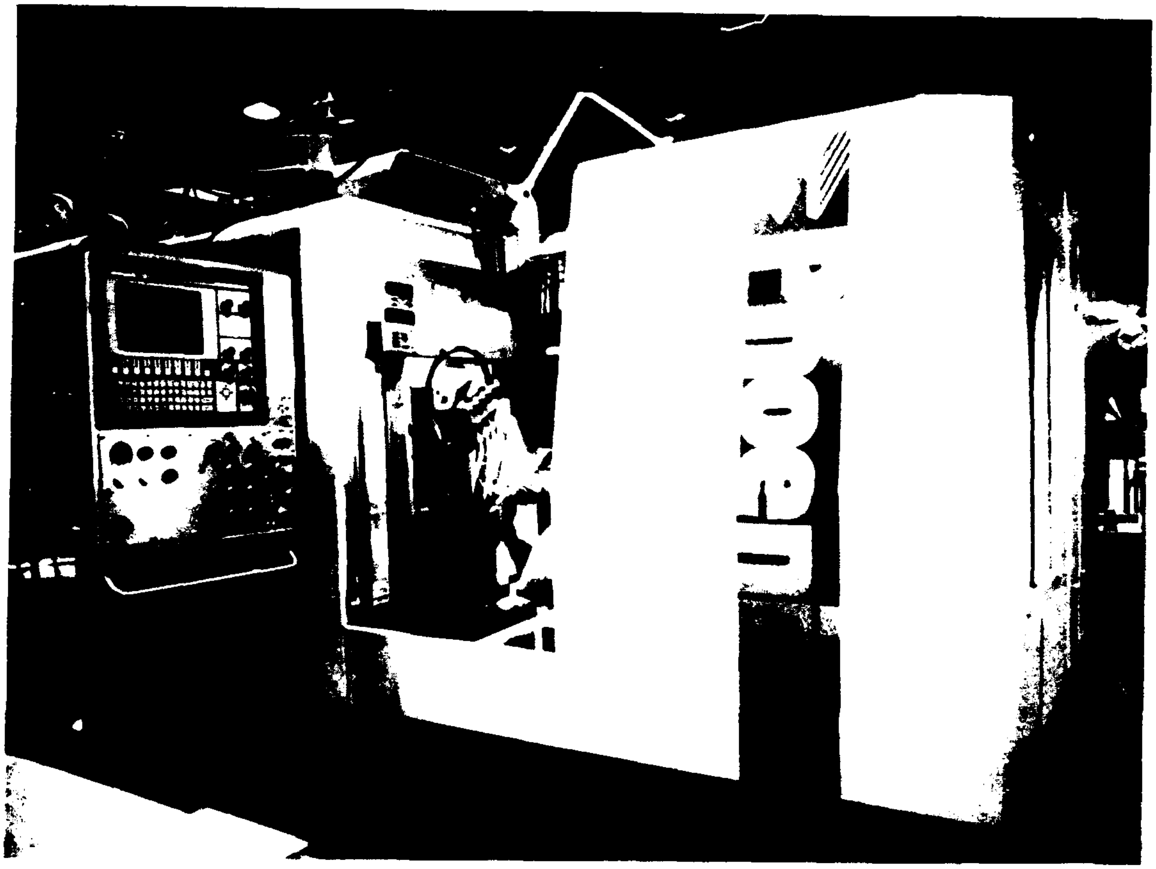


Figure 20 - The Phoenix 400PG CNC Bevel Gear Grinder

All six axes are simultaneously controlled by CNC control and software. This approach translates the basic motions required to generate a tooth form into the simplest linear and rotational elements. Programming is accomplished by user-friendly menus so that gear grinding summary data can be easily input from a keyboard or simply called up from the control memory. The mechanical setup adjustments, required on conventional gear grinding machines, have been eliminated. Set up time and machine changeovers are significantly reduced. As a result, operator efficiency is dramatically improved.

Set up time is accomplished virtually in minutes. Random batch and small lot size processing are as simple as calling up a program and mounting the appropriate tooling. Grinding wheel dimensions are simply entered into the control and the CNC then automatically calculates the movements and positions necessary to grind the gear.

Advanced communication links to a mainframe or personal computer are possible to allow setup, proportional changes, or corrective settings from the Gleason G-AGE software, automatically.

To further test the validity of the enhanced correction program, first and second order changes were made to the flank form by changing the theoretical setting data instead of grinding the actual gear. This method offers more flexibility in assessing the correction data since the physical problems associated with resetting the Gleason grinder are eliminated. The master gear and pinion were then measured on the Zeiss with the G-Age correction program. The correction program dictated machine setting changes to correct the errant flank form. This result, which was also noted in the earlier program, highlights the fact that the Gleason correction program can dictate two or more alternate setting-changes to correct one disturbed setting. The changes, dictated by the correction program, were made, precisely as indicated, and the gears remeasured. The results demonstrated that the indicated G-Age correction values did, in fact, correct the variance in the flank form.

Selected Gear Set No. 2.

The Gleason Summary, Dimension Sheet, TCA, and Special Analysis File (SAF) was also established for the second Selected Gear Set P/Ns 70351-08205 and 70351-08221. Attempts to adjust the SAF to duplicate the flank form of the master gear and pinion, as was done for gear set No. 1, however, were unsuccessful. The culprit was the gear member, P/N 70351-08221. In 1980, before the Zeiss machine was introduced as a vehicle to inspect spiral bevel gears, and before the on-line computer link-up with the Gleason Works, a change was made in the index interval and cam number for grinding this gear. This change produced a generating error in the flank of the tooth on the convex (drive) side which resulted in a severe undercut condition in the dedendum at the toe end of the tooth. This undercut can be seen in Figure 21. This condition was not discernable by the conventional testing methods in place at that time, and the gear was put into production. The SAF would not accept this undercut condition and attempts to overcome the difficulty, and develop correction data for this gear, were futile. The Gleason computer system doesn't accept a tooth form which has a generated undercut or has indicated machine settings which are outside their predetermined limits. Attempts were made to change the cam number and machine settings to values which the Gleason computer system would accept. These changes, however, caused a large discrepancy between the theoretical and actual part. It was finally determined that it would not be possible to establish correction data for this gear member. At this point it was proposed that an alternate gear mesh be used as the second selected gear set for this program.

Alternate selected Gear Set

Formal permission was received from the Contract Officer to substitute the BLACK HAWK/SEAHAWK Tail Take Off bevel gear mesh for the selected gear set #2. This mesh is also shown highlighted in Figure 12.

The Tail Takeoff Pinion and Gear Set, (P/Ns 70351-38167 and 70351-38151) selected as an alternate mesh has an increasing speed ratio of 3.409, rotates at an output speed of 4115 RPM, and delivers 524 horsepower to the tail rotor. The Special Analysis File (SAF) was

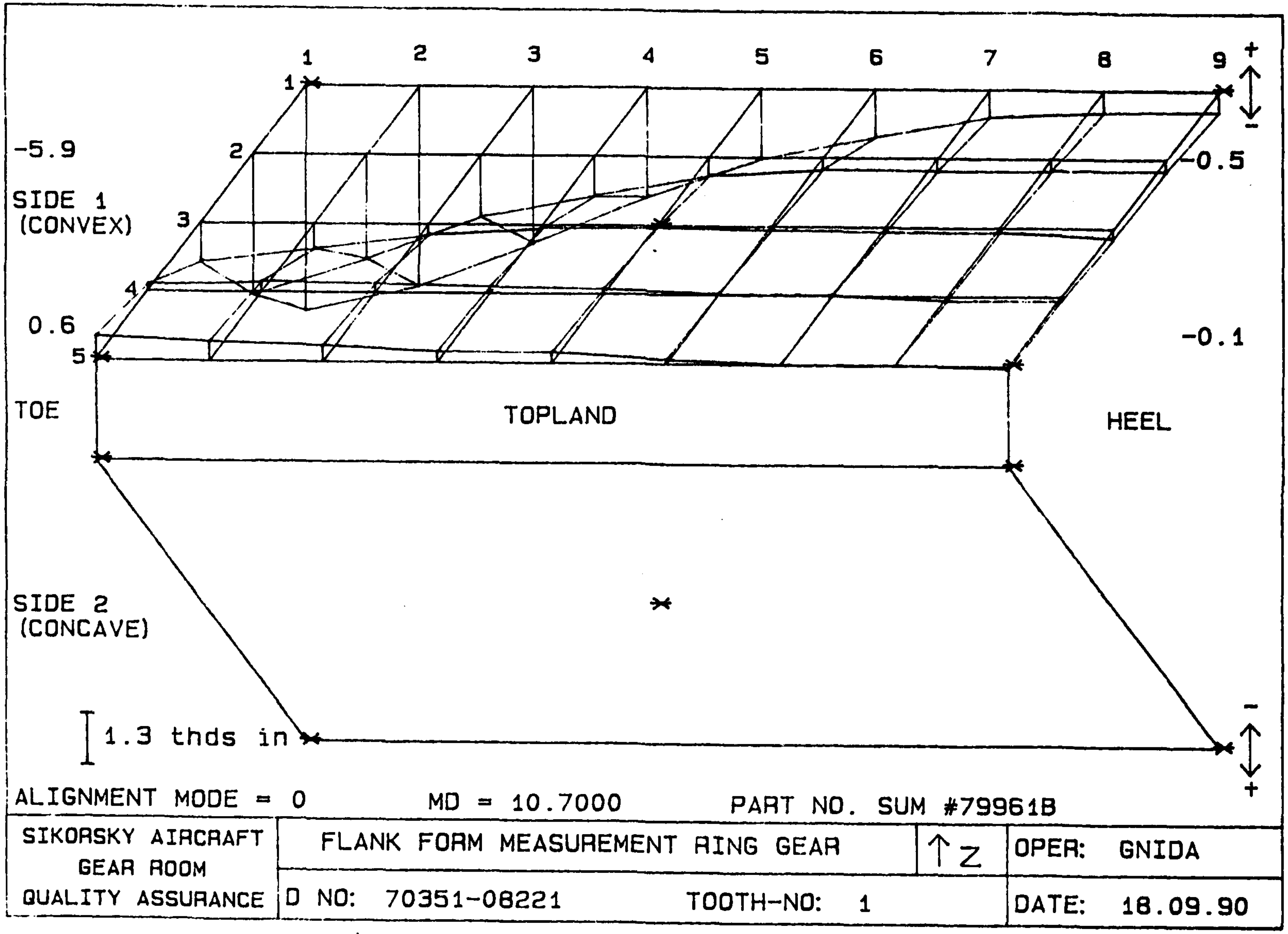


Figure 21 - Zeiss Plot of Gear Set No. 2

successfully developed for this gear set and the correction program satisfactorily demonstrated. The measurement results for this gear set are shown in Figures 22 and 23.

Concurrently with the performance of this development procedure, The Gleason Works, of Rochester, New York, as the originator and sole proprietor for the machine correction part of the RAM 300 program, made a number of changes to the software to improve its performance. Some of the more significant changes made are as follows:

1. A more convenient method for adjusting and correcting the basic settings in the Special Analysis File was provided.

2. More options in the correction data were included; such as:

   a). Zero First Order
   b). First Order
   c). First Order and Second Order
   d). First Order and Second Order with RC

3. Gears can be measured as they are ground; either Single-Side or Spread-Blade

4. Changes to the Eccentric Angle were previously indicated in degrees and minutes. Now the angle is given in hundreds of a minute, an accuracy which is required to properly control the flank form.

The final step in this task was to establish and store the nominal values for each component in the Zeiss™ HP computer on a floppy disc. This was done by digitizing each master gear and pinion at the same 45 grid points covering the gear tooth surface. These became the coordinate points representing the nominal gear tooth surface to which the production parts would be compared.

It should be noted that very small differences may exist between the nominal surface coordinates, represented by the master gears, and the theoretical coordinates, generated from the final machine settings. Since the master gear represents the desired profile, determined from developmental testing, the production parts are compared to the nominal values digitized from the master gears and deviations from these nominal values are calculated. The theoretical coordinate values are derived directly from the theoretical model located in the Gleason mainframe computer and are used in the corrective program to calculate the required machine-setting changes.

These theoretical values are developed by adjusting the basic settings in the SAF. This is accomplished by trial and error by measuring the master gear and pinion during each iteration and using the correction program to provide the necessary changes.

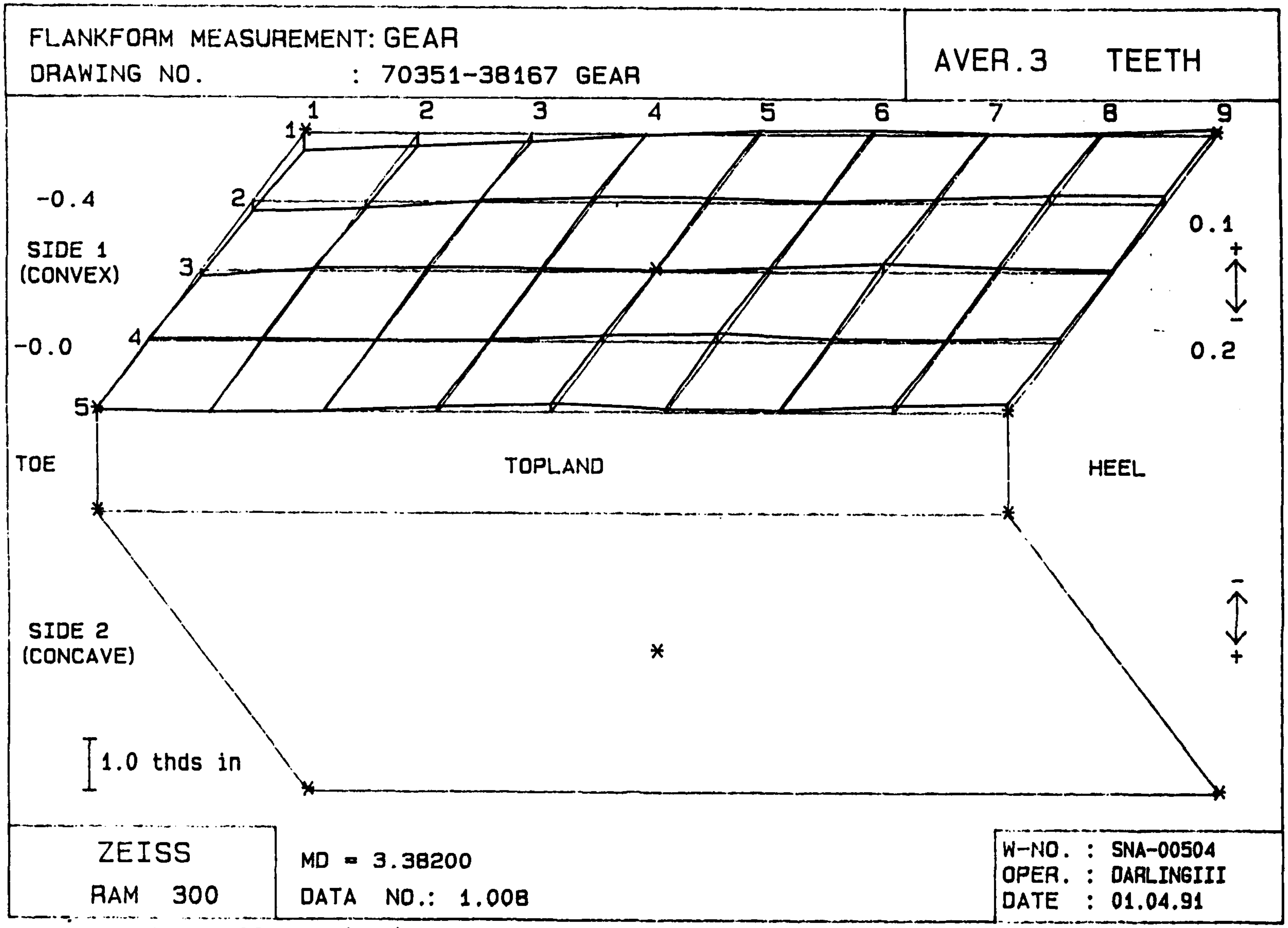


Figure 22 - Zeiss/Gleason Measurement Results - Alt. Pinion Corrected

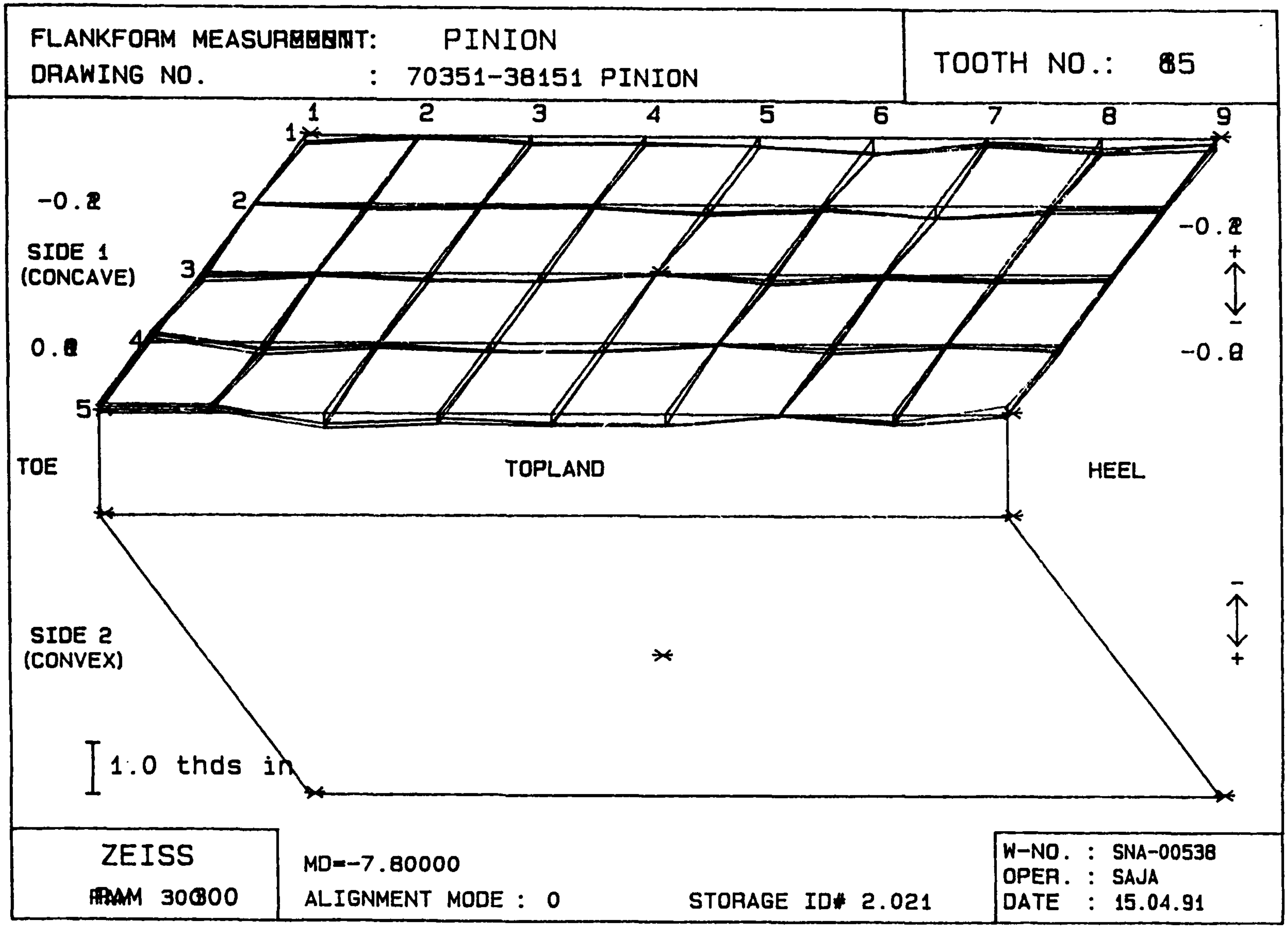


Figure 23 - Zeiss/Gleason Measurement Results - Alt. Gear Corrected

Task 4 - Verification of the Enhanced Corrective Process

To verify the enhanced corrective process, which now includes the automated second-order change capability, a pinion and gear for each selected gear set were followed through the production process.

The machined gears were set up in the Gleason grinder and ground to finish dimensions. The gears were then measured on the Zeiss™ machine and reground as indicated by the grinding machine changes calculated by the enhanced correction program. The pinion and gear were then remeasured to verify that the indicated changes were effective. The man-hours expended for each of the required steps during the enhanced spiral bevel gear manufacturing/inspection process were recorded and are shown in Table 1. Figures 24 and 25 demonstrate the Zeiss/Gleason measurements of P/N 70351-38114 and pinion P/N 70351-38104 after developing the flank form using the enhanced Gleason correction program. Similar plots are shown for the alternate gear set in Figures 26 and 27.

After final grinding, the selected gear sets were processed and assembled into a production main gearbox and a production acceptance test (ATP) conducted.

The ATP is an integrated gearbox system back-to-back test run on the UH-60 main gearbox (see Figure 28) in the UH-60A Test Facility before it is installed on the aircraft. Since this test is part of the production qualification process, the test gear box is not disassembled for detail inspection unless there are signs of surface distress, or excessive concentrations of load, such as scoring, surface pitting, or chipping.

All gears and pinions which were ground and measured using the Zeiss/Gleason enhanced correction program have demonstrated good performance in the production gearbox, and none were the cause of gearbox rejection.

Task 5 - Economic Analysis

Based on a manufacturing gear lot size of 20 gears, the projected savings in inspection and manufacturing time realized from the installation of the enhanced measurement process described herein was estimated to be 1.72 hours per gear. The following analysis shows the equivalent dollar savings and resulting cash flow over a five year period.

Basis for Economic analysis

The data upon which the economic impact of the enhanced spiral bevel gear inspection process is based is shown in Table 2. It assumes that 50 percent of the BLACK HAWK and SEA HAWK spiral bevel gears are produced at Sikorsky Aircraft, and estimates the benefits derived solely from that production for each year.

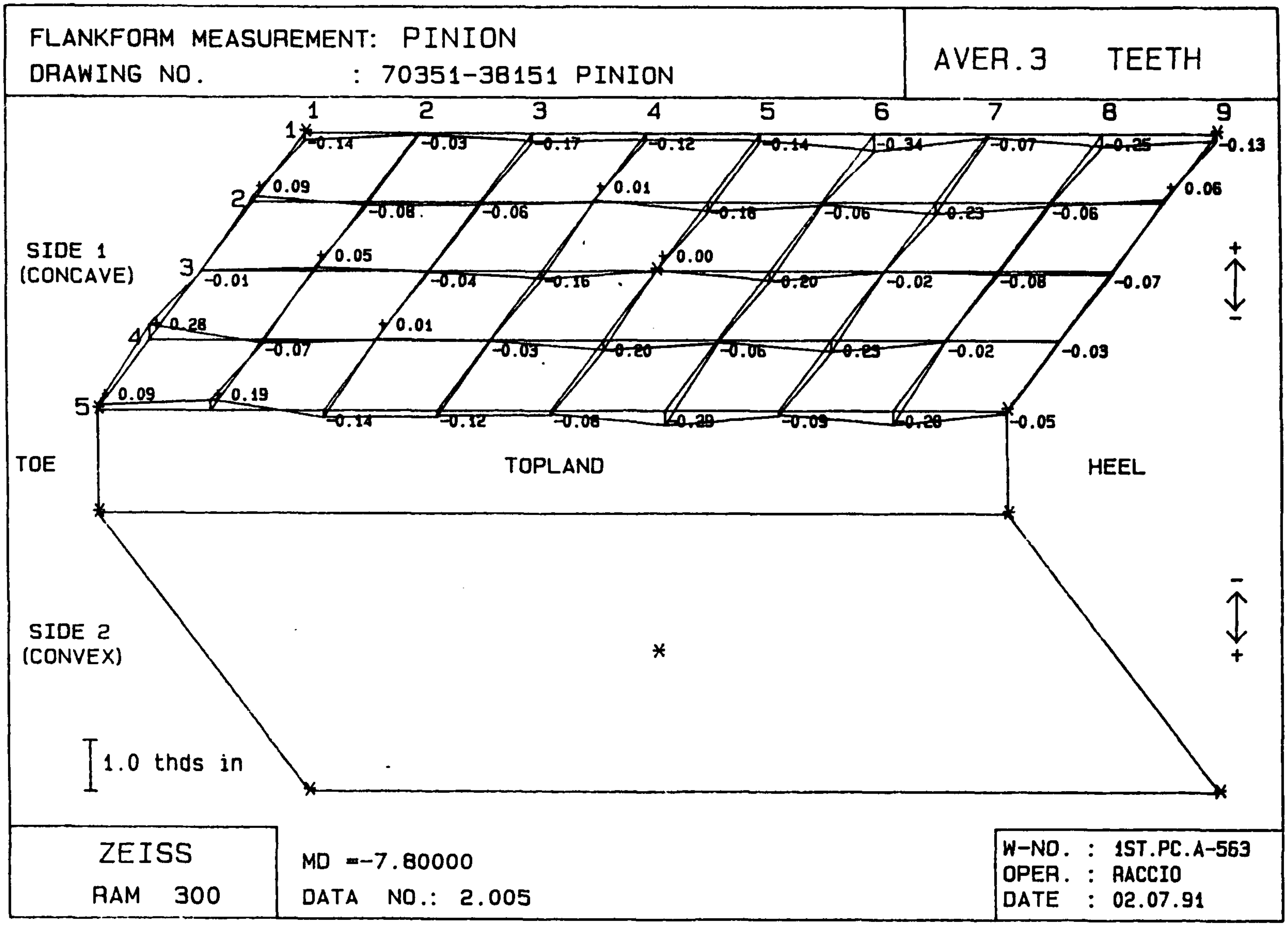


Figure 24 - Verification Measurement Results - Gear, Set No. 1

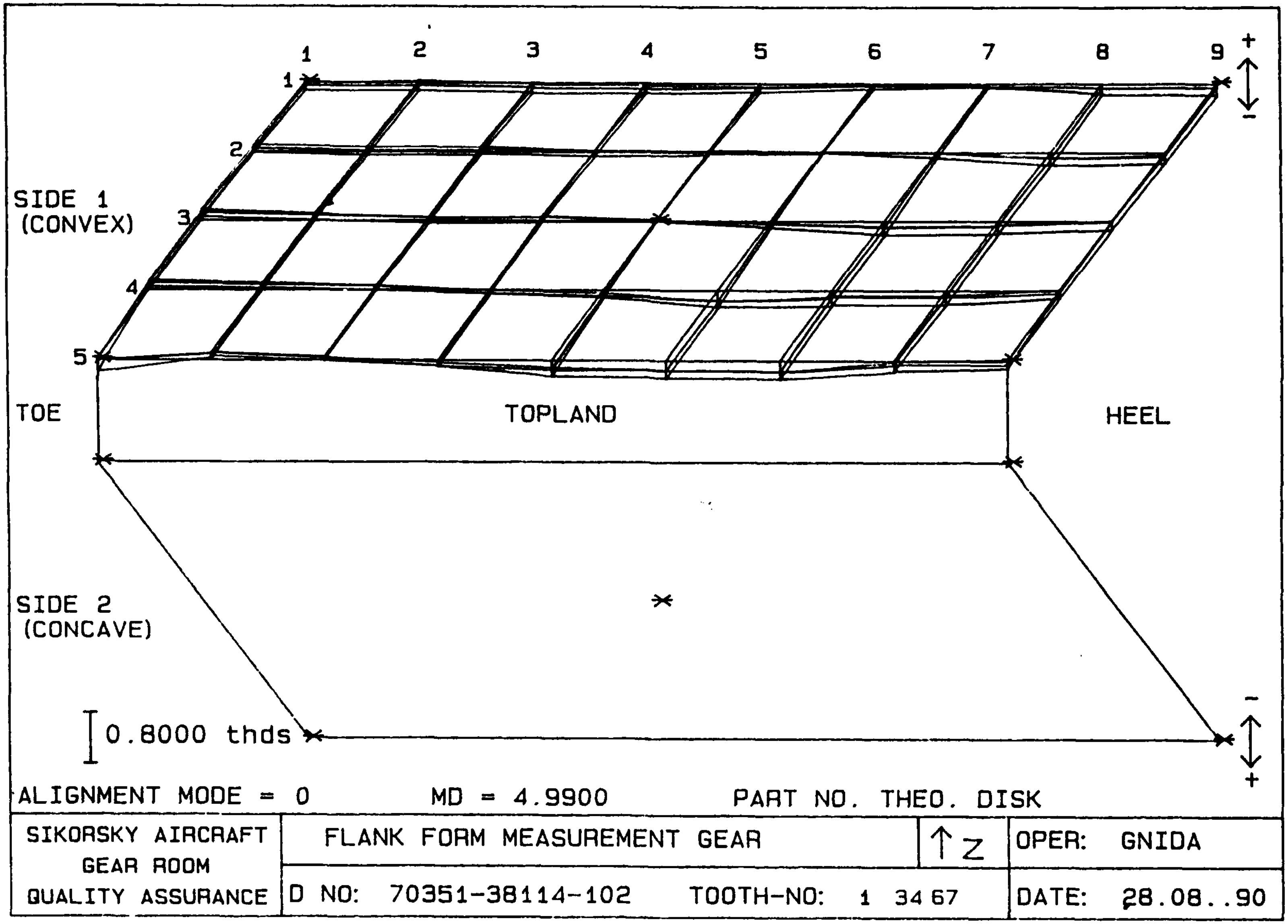


Figure 25 - Verification Measurement Results - Pinion, Set No. 1

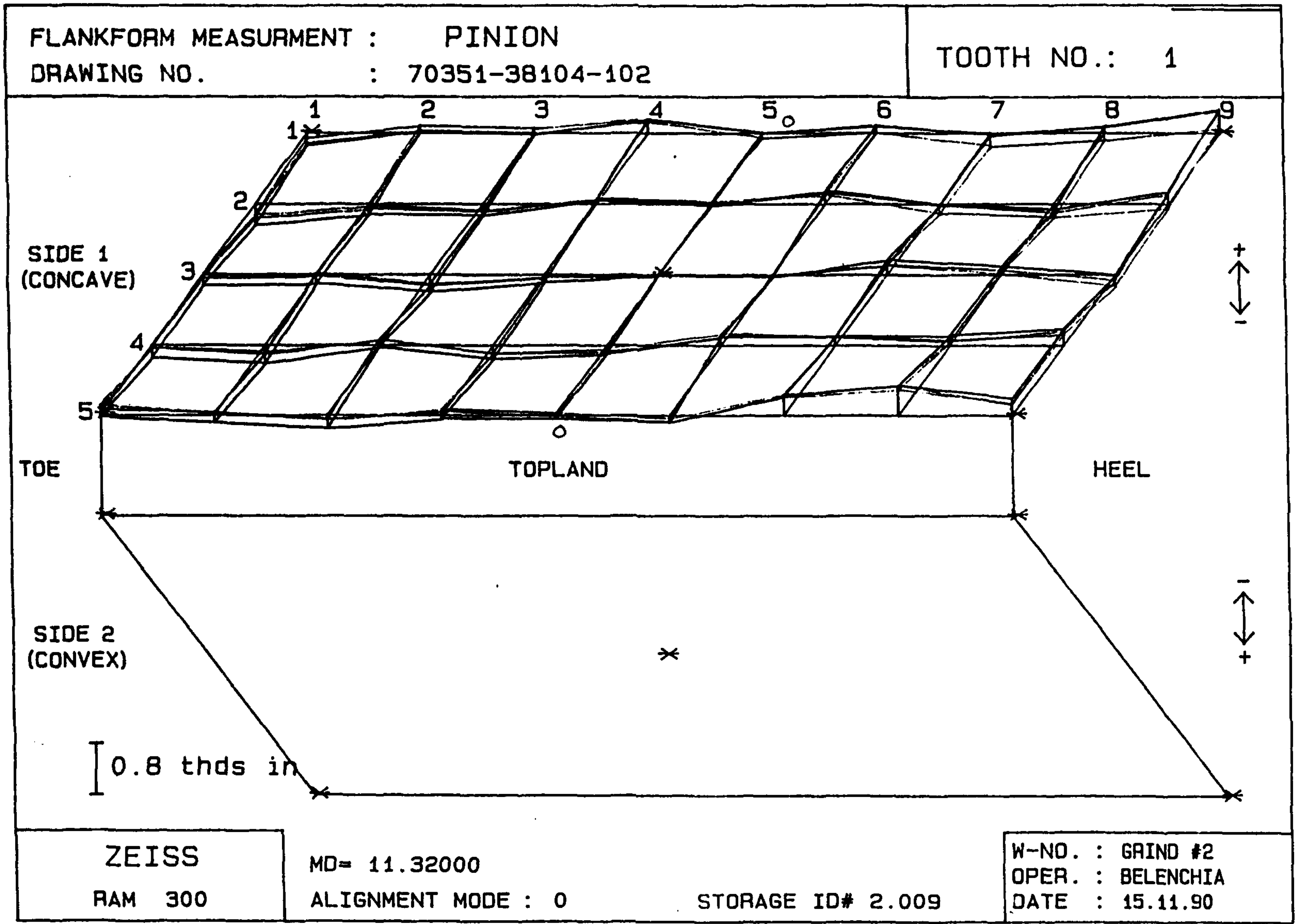


Figure 26 - Verification Measurement Results - Gear, Alternate Set

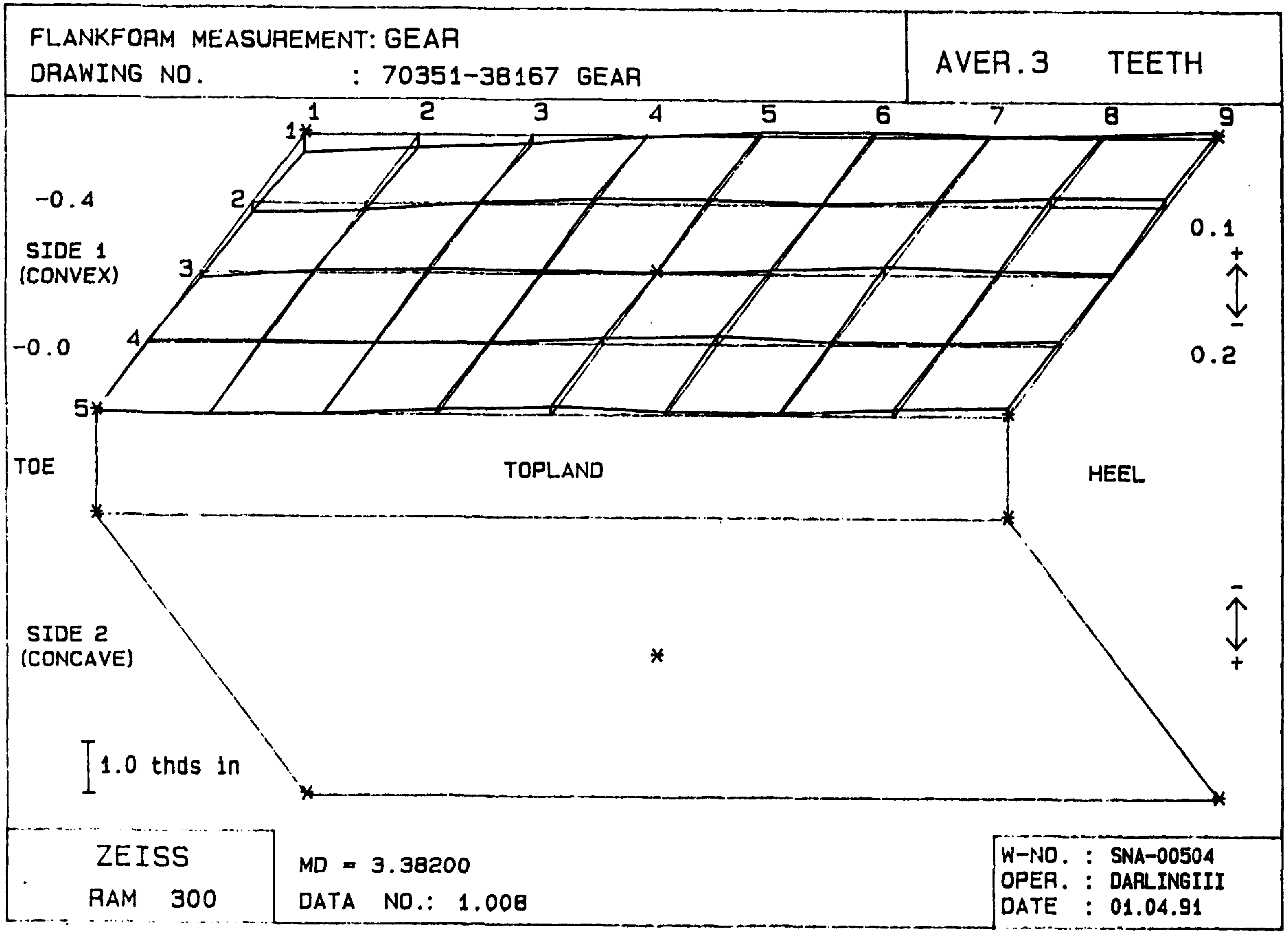


Figure 27 - Verification Measurement Results - Pinion, Alternate Set

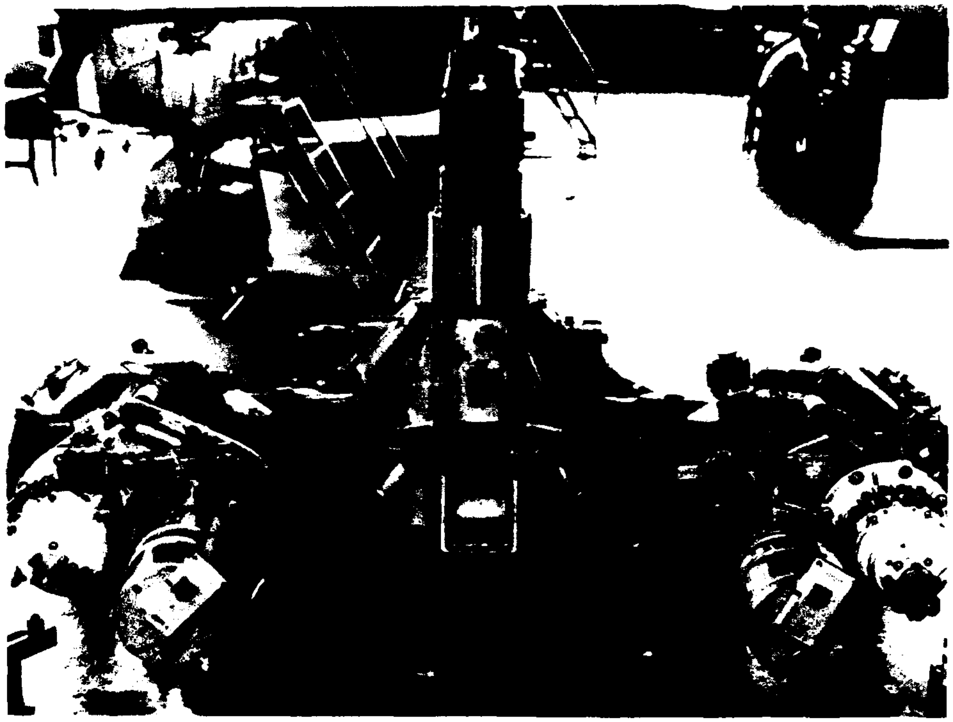


Figure 28 - UH-60 Test Main Gearbox

TABLE 2. BASIS FOR ECONOMIC ANALYSIS

No. of aircraft - BLACK HAWK, SEAHAWK, spares

year	1	2	3	4	5
A/C	158	163	163	163	158

17 bevel gears per aircraft
50% of gears produced at Sikorsky
1.72 hrs saved per gear
Labor rate - $14.48 per hour (1991 dollars)
Overhead rate - 223%
Tax bracket - 40%

Income/Expense Statement

Table 3 lists the annual dollar savings and costs associated with the enhanced inspection method in each of the five years. Table 4 presents the annual and cumulative cash flow situation.

Discussion of results

It has been demonstrated, in this program, that the automatic calculation of both first and second-order grinding machine changes works very well, especially in conjunction with the new class of CNC bevel gear grinders represented by the Phoenix 400PG. Verification

TABLE 3. INCOME/EXPENSE STATEMENT

	Base yr 0	Base yr 1	Base yr 2	Base yr 3	Base yr 4	Base yr 5
Savings:						
Labor hrs		33448	34507	34507	34507	33448
Overhead		74590	76950	76950	76950	74590
Total Savings		108038	111457	111457	111457	108038
Costs:						
Depreciation						
Property tax						
Maintenance						
Supplies						
Miscellaneous						
Total Costs		0	0	0	0	0
Gross Margin		108038	111457	111457	111457	108038
Start-up expenses		0	0	0	0	0
Pre-tax prof/loss		108038	111457	111457	111457	108038
Aft-tax prof/loss		64823	66874	66874	66874	64823

TABLE 4. CASH FLOW ANALYSIS

	Base yr 0	Base yr 1	Base yr 2	Base yr 3	Base yr 4	Base yr 5
Pre-tax prof/loss:		108038	111457	111457	111457	108038
Aft-tax prof/loss		64823	66874	66874	66874	64823
Total Savings		64823	66874	66874	66874	64823
Annual cash flow		64823	66874	66874	66874	64823
Cumulative cash flow		64823	131697	198571	265445	330268
Present Worth @ 23%	185083					

measurements on two selected production gear sets have shown that the bevel gear tooth profile can be held to within acceptable limits with only one or, at the most, two iterations.

The inclusion of the automatic second order change capability has resulted in an additional savings of 1.72 labor hours per gear.

Based upon the cash flow picture presented in Table 4, the calculated present worth, with an assumed acceptable rate of return of 23 percent, is $185,083 for this second order change enhancement.

Based upon the success of this program, the final step in the automated inspection process for spiral bevel gears is now possible. This involves a closed-loop or hard-wire interface system linking the Zeiss coordinate measuring machine with the Gleason CNC Pheonix gear grinder. This completely automated system is expected to be in place at Sikorsky Aircraft within the next three years.

CONCLUSIONS

1. An enhanced inspection method for spiral bevel gears involving automatic first and second-order change capability was demonstrated and verified.

2. The validated process automatically calculates first and second-order grinding machine setting changes necessary to correct an out-of-tolerance spiral bevel gear tooth profile in only two grinding cycles.

3. Manufacturing and inspection time for spiral bevel gears is reduced by 1.72 hours per gear, resulting in significant cost savings.

4. The enhancement was demonstrated on two selected BLACK HAWK/SEAHAWK gear sets on both the Gleason #463 and the Phoenix 400PG grinders. The process worked much better on the CNC Phoenix with fewer grinding iterations.

5. All gears inspected with the enhanced process were subjected to a final ATP test in a production gearbox without any signs of surface distress or abnormal distribution of load.

6. The technology developed in this program can be applied to all bevel gears manufactured by Sikorsky Aircraft and Suppliers which use the Zeiss/Gleason system.

7. This technology was required to permit the successful operation of the Phoenix Grinder.

8. The enhanced inspection system will produce higher-quality gears with fewer anomalies in acceptance test results.

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13. ABSTRACT ***(Maximum 200 words)***
This report presents the results of a Manufacturing Methods and Technology program to define, develop, and evaluate an enhanced inspection system for spiral bevel gears. The method utilizes a multi-axis coordinate measuring machine which maps the working surface of the tooth and compares it to nominal reference values stored in the machine's computer. The enhanced technique features a means for automatically calculating corrective grinding machine settings, involving both first and second order changes, to control the tooth profile to within specified tolerance limits. This enhanced method eliminates the subjective decision making involved in the tooth patterning method, still in use today, which compares contact patterns obtained when the gear set is run under light load in a rolling test machine. It produces a higher quality gear with significant inspection time and cost savings.

14. SUBJECT TERMS
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