MACH 6 ELECTROFORMED NICKEL NOZZLE REFURBISHMENT

FNAS Investigation of Ultra-Smooth Surfaces

NAS8-38609

UAH D.O. 007, 5-32762

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(NASA-CR-184299) MACH 6 ELECTROFORMED NICKEL NOZZLE REFURBISHMENT: FNAS INVESTIGATION OF ULTRA-SMOOTH SURFACES Final Report, Aug. - Nov. 1991 (Alabama Univ.) 59 p

N92-21494

CSCL 21H G3/20

Unclas

0078066

NASA National Aeronautics and Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

1) Mach 6 Electroformed Nickel Nozzle Refurbishment

2) FNAS Investigation of Ultra-Smooth Surfaces

5. Report Date
January 30, 1992

6. Performing Organization Code
5-32762

7. Author(s)
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8. Performing Organization Report No.
FINAL REPORT

10. Work Unit No.

9. Performing Organization Name and Address
University of Alabama in Huntsville
Center for Applied Optics
Huntsville, AL 35899

11. Contract or Grant No. D.O. 007
NAS8-38609 & 36955

13. Type of Report and Period Covered

12. Sponsoring Agency Name and Address
(1) Marshall Space Flight Center
(2) Langley Research Center

14. Sponsoring Agency Code

15. Supplementary Notes

Delivered Mach 6 Nozzle to Langley

16. Abstract

This task is in support of the Quiet Hypersonic Wind Tunnel effort currently in effect at NASA Langley Research Center, VA.

The task objective has been to apply a coating of nickel-phosphorous alloy by catalytic deposition and then polish and inspect the inside surface using optical device processes.

17. Key Words (Suggested by Author(s))
Hypersonic Wind Tunnel
Polish
Nickel-Phosphorous Plating

18. Distribution Statement

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
none	none	60	

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MACH 6 ELECTROFORMED NICKEL NOZZLE REFURBISHMENT

ABSTRACT

This task is in support of the Quiet Hypersonic Wind Tunnel effort currently in effect at NASA Langley Research Center, VA.

A laminar flow wind tunnel nozzle has been previously fabricated by electroforming pure nickel over a two piece mandrel which was removed. The nozzle was then pressed into a stainless steel jacket for rigidity. The original nickel surface was a replication of the polished mandrel but had degraded due to oxidation. The inside surface requirements are very stringent in order to achieve laminar or quiet flow at the specific design of Mach 6. The throat area of the axisymmetric device must have a surface finish with no defects greater than 16 microinches. This requires an RMS average background of about four microinches or better for inspection purposes.

The task objective has been to apply a coating of nickel-phosphorous alloy by catalytic deposition and then polish the inside of the nozzle retaining dimensional and surface finish tolerances as specified per drawings supplied. Since the unit is not an optical component, conventional optical inspection methods for surface finish and figure are not readily achieved. Measurements have been made using surface profilometry and surface quality analysis were by statistical and FFT methods.

Two separate plating efforts and three concerted polishing efforts are described.

SCOPE

The intent of this task was to apply a very hard, fine grain structure metal alloy of nickel-phosphorous. This alloy is much more durable than pure nickel and typically can be polished to a finer finish with less difficulty due to the amorphous nature of the deposit.

Nickel-phosphorous can be deposited very uniformly at about four ten-thousandths of an inch per hour from catalytic processes. This uniformity depends primarily on sufficient mass transport of the heated solution to the part to permit the maximum diffusion limiting nickel alloy deposition rate. Since the part is essentially conical in shape, the surface area varies considerably with a given axial segment. Thus the primary concern with the plating was forcing enough solution through the inside of the part to maintain uniform plating.

Several candidate vendors were surveyed for the plating and the only response was Metal Surfaces, Inc., Bell Gardens, CA. MSI has a good reputation for military standard compliance plating and had sufficiently large processes in place for the 350 pound nozzle. A suggested process was forwarded but MSI chose not to follow it explicitly, based on standard processes in place and a high assurance of success. The primary concerns were adhesion and pitting of the deposit. MSI stated that it would be impossible to strip the electroless Ni-P alloy from the nickel nozzle. Also, they were only confident that the adhesion would be adequate if internal standard procedures were followed. A second smaller electroformed nickel part (Mach 5) was included in the purchase order and was used as a test vehicle. This component was successfully plated by MSI prior to plating the Mach 6 unit.

Lapping was to be performed by the Marshall Space Flight Center, Optics Fabrication Branch using lapping tools fabricated and contour-machined with precision CNC single point diamond machining at the University of Alabama in Huntsville.

DESCRIPTION

Plating:

The plating was specified to be 0.0015 - 0.0020 inches thick. The preferred alloy is high phosphorous of 10% by weight or more to facilitate lapping. This alloy produces a fine grain structure, approaching an amorphous structure. The formation of non-uniform phosphorous distribution is also minimized. Non-uniform alloy deposition can cause diffusion of phosphorous in non-uniform rosette patterns upon heating subsequently affecting the final polishing quality. The alloy plating process was not stated by MCI.

The requested plating process was to clean and then activate the nickel surface for plating by immersion in 25% HCl, 25% H_2SO_4 and 50% water at 110-120 Deg. F. This will remove the nickel oxide film which forms spontaneously on the nickel. The vendor, however, chose a more heuristic approach of applying a thin film of pure nickel from a dilute nickel chloride - HCl solution which deposits nickel at a very high reduction potential which reduces the oxide and permits an adhesion layer to be deposited in about one or two minutes. Subsequent plating in the electroless Ni-P will be quite adherent.

Unfortunately the "NiCl strike" process required inserting an electrode (anode) inside the nozzle and application of a rather high current of 50-100 amperes. Inadvertently and not known to the vendor, the electrode apparently touched the side of the nozzle in three places within the narrow region just behind the throat. This caused three areas of damage in the form of a cluster of small pits. When the nozzle was received after plat-

ing, the decision was to attempt lapping due to the difficulty involved with stripping nickel phosphorous alloy from the pure nickel nozzle. MCI stated they would not be able to strip the part for replating.

The lapping process took several weeks and was not able to remove the serious pits. Also, large nodules not inherent in an electroless nickel process had occurred on the sharp lip. The cause of this has not been determined but may have been manifested by the use of the electrolytic NiCl process due to a very high current density locally on the lip. Since the NiCl process is a diffusion limited process to permit the highly cathodic reduction potential the formation of crystalline dendrites occurs under conditions of excessive current density. The nodules on the lip were removed by hand polishing which was very time consuming. The small Mach 5 unit did not suffer the same damaging defects.

After several weeks of lapping effort, it was apparent that the nickel phosphorous alloy must be removed from the pure nickel and replated. This was a serious problem in that the two materials are very similar in chemical dissolution behavior.

Nickel metal is subject to passivation at high oxidation potential in an oxidizing media. Phosphorous will actually improve this oxidation resistance to corrosion in the general environmental sense. However, by increasing the oxidation to much higher values than would be normally encountered in any environment, a reversal takes effect. The phosphorous alloy will then begin to dissolve while the pure nickel will further passivate. Since the nickel was encased in stainless steel, the nickel would remain slightly anodic when immersed in solution. This is due to the galvanic coupling and the noble nature of the nickel-iron-chromium alloy casing (Fig 1). Tests were performed on nickel plated, nickel-phosphorous over-plated samples. By using a very concentrated nitric acid solution it was possible to remove the alloy coating from the pure nickel deposit on these samples. Above 65% nitric acid (commercial azeotrope) the pure nickel dissolution was less than 0.0001 inch/Hr. Thus the decision to strip the part was agreed upon.

VERVAL, Inc., subcontractor to NASA MFSC, performed the stripping and replating. The stripping took about 3 1/2 hours and several anomalies were noted as the process proceeded. The throat region which had significant lapping away of metal took much longer than the bulk of the part to strip. This may have been due in some unidentified way to the polishing but appeared more likely to have been an intermediate deposit of pure nickel sandwiched between two layers of nickel-phosphorous alloy. Additionally, the defects in the throat region were still evident after stripping the alloy. The cause of the pits had evidently

also damaged the base nickel. These defects were therefor dressed by hand polishing for several hours to remove and blend to the surrounding surface.

The electroless nickel phosphorous alloy was deposited the second time from a commercial solution (Enthone-418) which with the pH adjusted to 4.5, produces an alloy of 8-10% phosphorous. The hardness is about 52-54 Rockwell C and may be increased by heat treatment at 750 Deg. F to about RC 60-62. The part was heated to 320 Deg. F for four hours to assure relief of any absorbed hydrogen during metal stripping and plating operations. This should result in a hardness of about RC 55. Approximately 0.004 inch of deposit was plated. The plating was performed by using chemical activation only. That is, no electrode needed to be placed inside the part. A solution of 20% HCl, 20% H_2SO_4 and 60% water was used for 10 minutes at 100 Deg. F. The part would not fit vertically in the VERVAL plating tank and so the operator had arranged a pump to force solution from the bottom upward. The part was placed in the tank with the throat down at about 45 degrees and continuously rocked by hand to release hydrogen bubbles forming along the high side of the plating surface.

This however turned out not to be adequate and after 9 1/2 hours of plating an area of lighter, dull plating about 3/4 inch wide could be seen along most of the distance through the part. This area was apparently shielded from appropriate mass transport of solution by the hydrogen bubbles enough to disrupt proper plating. The decision this time was that the plating was considerably better than before and would probably polish well although extra effort would be required to alleviate any problems due to the streak of dull plating.

Polishing:

The contour of the nozzle interior surface was replicated on two lapping heads manufactured by MSFC. The precision dimensional control was done by UAH using a Rank-Pneumo single-point diamond turning center. The lap faces were made of porous polyurathane plastic from Rhodel which were replaced with Buehler lapping pads for the final polish.

The lapping was initially performed in four stages using alpha Al_2O_3 from Microgrit, Buehler or Baikowski Industry. The first grit size was 3.0 μm. This was used until a uniform surface was observed. Next the grit was changed to 1.0 μm followed by 0.3 μm and then 0.05 μm for final abrasive polish using the Buehler face pads. A final very fine polish was completed using colloidal silica gel. This removed the fine scratches left by the alumina polishing steps.

This process was completed using the machined pads for the first plating from Metal Surfaces, Inc. The continuous rotation at a fixed axial position caused some tendency toward rings due to the edges of the laps. Overlapping the edge effects was very difficult since even slight axial movement changed the contour fit of the laps to the nozzle. Also the overlapping area was not wearing at the same rate. Note that one lap was used from the front and the other from behind. The large lap which was used from the exit end of the nozzle extended back about eight inches from the throat. The critical throat area was subjected to about twice the wear due to the overlap. A small CCD camera was borrowed from the Army and did reveal the defects but made no provision for quantifying defect depth.

The first plating and polishing attempt failed to produce the needed surface due to plating defects as previously described and eventually the electroless nickel-phosphorous alloy was partially lapped through to the pure nickel. At this time the rings were about fifty microinches in step size.

After stripping and replating the part as described, the lapping process was changed. Commercial cylinder hones were purchased and modified. The stones were removed and plastic (nylon) pads were machined and attached in place. The lapping face material and media was used as previously. The laps were rotated either with a milling machine operating horizontally or with a 1/2 inch drive drill. A small hone was used for the narrow throat area and could be drawn about three inches. A larger hone was used to polish about 35 inches of the wind tunnel. The forward section from the throat was polished by hand using the described processes. The surface profile was compared to the original data set (Fig. 2).

Upon attaining a reflective surface it was evident that the nozzle had a discrepancy not apparent at the time of inspection after plating. About 15 degrees off each side of the streak of dull plating mentioned previously, a series of low period waves were observed. These waves were evidently of two frequencies and were related to the solution transport in the nozzle as the solution was slowly pumped upward through the nozzle. Subsequent profilometric inspection in the throat region showed the forward eight inches of the nozzle to be better than the remaining 32 inches. The waves in the throat were about one micrometer in height with a period of about one millimeter. The waves back into the nozzle were worse but could not be measured with the existing profilometer available to UAH. The small CCD camera previously used to view the inside of the nozzle could not resolve the height of the defects. These waves were still evident after sufficient lapping to polish the surface of the surrounding material. Due to an extremely tight schedule resulting from the rework requirements, the decision was made to ship the part for testing in place at Langley. See Figures 3 and 4.

The performance of the wind tunnel nozzle was not satisfactory due to the waves. The unit was therefor returned to MSFC for additional work. Again serious decisions involved the additional removal of material regarding the thickness and integrity of the final part.

The lapping process was repeated in the large section of the tunnel using the modified hones. A portable Taylor-Hobson Surtronic 3-P profilometer was obtained and used to assess the progress of the reduction in amplitude of the waves. The polishing was initiated with a coarser lapping compound of 5μm alumina and the lapping pads were modified to reduce edge effects. The same sequence of polishing as before was then repeated. After about eight hours of accumulated lapping time with the three and five micron polishing compound the waves were significantly reduced as measured with the small portable profilometer. At this point the amplitude of the waves was measured at the polishing station, to be about 50 microinches peak to valley. Subsequently another 1.5 hours with the five micron and 1.0 with the 3.0 micron polish reduced the short period waves to about 10 microinches and the longer period waves of about 1/2 inch period appeared to be reduced to about 25 microinches (Figure 5). At this time a significant improvement could be seen by observation. However the dull band of plating mentioned earlier was apparently lapped through to the original pure nickel.

Also due to the amount of time of polishing, the front section was not well matched to the re-polished area. When the small area of the throat was lapped to blend the polishing in the larger area, two pits appeared. These were plated with copper as before and subsequently polished with the small hone and also by hand. At this time it appeared evident that the nickel-phosphorous alloy was wearing through to the base nickel at the same region as the dull streak had originally been. Therefor the polishing media was limited to the 0.05 micron alumina and the colloidal silica gel beyond this observation.

Inspection:

In-process inspection was performed during the first plating and polishing attempt using a CCD camera system borrowed from the Army. This unit permitted observation of the surface quality but did not quantify the depth of any defects. Also the waves were not as readily discernible as by low angle observation with sufficient illumination. The unit was sufficiently sensitive however to readily observe scratches and the plating defects from the first vendor. This unit was not available for the subsequent plating and polishing work. For the subsequent in-process inspection the Taylor-Hobson Surftronic 3-P was used. This unit could be used from the back by adding an extension bar to the probe permitting measurements to be taken from about five inches

back from the throat to the back of the part. This data was of sufficient quality to measure ripple and waviness at about 5-10 microinches peak to valley.

Quantitative measurements were taken on each of the three lapping efforts using the Taylor-Hobson, Talysurf, laser interferrometer surface profilometer at UAH. The data from the second and third polish was exported to an IBM PC format and subsequently refined by using Sigma Plot and Table Curve (Jandel Corp.) and also entered into MathCad (Mathsoft INC.) algorithms to determine the waviness by use of FFT and autocorrelation. The fit of the data to the original data was done using Sigma Plot to superimpose the measured contour upon the original data set. It was necessary to use a word processor to format the data.

Due to the awkwardness of the large piece and the extreme sensitivity of the measurement device, three measurements were taken using both a 0.5 mm diameter ruby stylus and a very sharp pointed diamond stylus. The instrument software does not permit waviness or Ra value calculations with the ruby stylus so the data must be carefully analyzed in other ways. Data from the diamond stylus was more limited in range, however good short order and microscopic surface detail can be readily ascertained from the instrument software. Much of the difficulty in analyzing the data directly on the Talysurf computer is due to the non-symmetrical shape when scanning over the throat, the software cannot fit the compound convex data to a convex or even aspheric shape. The use of the Table Curve software allowed curve fitting to a high order polynomial but as mentioned by Langley scientists the data must be further analyzed in the vicinity of any inflection for residual error. This was found to be from 0.0001 to 0.001 inches of calculation error for the polynomial set selected by the program. The polished part was found to be within about +/- 0.001 inches of the original data at all measured points. The surface finish is about 1 - 2 microinches Ra in the region measured. See Figures 3 through 7.

TABLE 1

Surface Finish - Polish 2; November 1991

Diamond Stylus 2 mm scan, Waviness Apparent;

Amplitude	=	+/- 0.900 μm
Period	=	1.000 mm
RA	=	0.210 μm
RMS	=	0.274 μm
Peak to Valley	=	1.789 μm

Diamond 0.2mm Scan

Peak to Valley	=	0.514 μm

Surface Finish - Polish 3, December 1991 Minimal Waviness;

Amplitude	=	0.880 μm
Period	=	1.000 cm
RA	=	0.034 μm
RMS	=	0.043 μm
Peak to Valley	=	0.249 μm

See Figure 3 and 4.

Analysis of the data with the slope minimized by forward difference subtraction to allow close examination shows the measurements to be sensitive to minor disturbances such as touching the table which the device rests on. By analyzing the motion of the profilometer also by forward difference to remove most of the tilt, it was shown (second effort) that an artifact first believed to be a scratch was evident on the X or traveling arm data at the same point that the measurement data indicated. This was apparently due to an inadvertent disturbance of the device during the measurement and not a scratch at all. See figures (5a-e, & 6a-f).

FFT analysis of the data shows an improvement of the third polishing (Jan.) effort over the second (NOV.) effort. This shows as the number of frequency spectra and spectrum amplitude increase for the rougher surface. The occurance of two or more frequency spectra may very well indicate the surface finish produced by more than one polish media. If the scratches are not completely reduced to the subsequent mark size the occurance of the frequency spectrum of each would be expected to show. The third polishing effort appears to have a significant improvement in this regard over the second. No measurements were taken for the first polishing attempt due to the poor quality of the coating and the obvious need to strip and replate the nickel phosphorous alloy.

After the last polishing effort it was noted that the deviation of the measured actual part surface from the data set was about 0.0006 inches within an inch measurement which exceeds the print requirement. This was a single gradual slope change over the measured distance. This was not resolved until the part was shipped. It would have been very difficult to have corrected this error due to all the lapping using the two different tools. To correct for this it would be mandatory to have the inspection at the lapping site for frequent measurement and analysis. This was considered, but not permissible by the University due to other commitments for the equipment.

SUMMARY

Accomplishments:

The surface of the nozzle has been coated with a nickel-phosphorous alloy of sufficient hardness and corrosion resistance to improve the durability. Due to plating defects which are clearly process related and not inherent, the final polished part was less than the desired quality. Surface finishing processes and lapping media were identified which produced a sub-micron surface finish on the interior plated surface. Defects apparently manifested by the first plating attempt were repaired using a small brush plating process demonstrating that individual small defects can be repaired. Measurement and analysis by profilometry, demonstrated that quantitative control of the surface can be achieved. Total surface inspection was not possible.

Recommendations:

In order to absolutely refurbish this very difficult part to the quiet configuration surface perfection, it will be necessary to once again strip and replate the part. Under no circumstance can the plating process requirements be compromised due to lack of available equipment or process validation. This will require a vertical holding fixture and a plating process large enough to hold the part vertically. The process must have sufficient pumps and plumbing by design to continuously supply an abundance of agitation to the interior of the part throughout the process. Filtration must be continuous even during the plating operation.

The chemical activation process used the second time provided adequate adhesion and the recommendation is that should the part be replated that the "strike " process with an electrode not be used. A very accurate temperature controller is required and solution replenishment during the plating process is mandatory unless a very large process is used. The use of chromium instead of nickel- phosphorous may be considered but tests would need to be performed. In the case of chromium plating, an anode is mandatory and a special design is required to avoid any chance of striking the part and damaging the surface.

Careful machining of lapping heads for the hones will provide a suitable lapping mechanism. A third size intermediate lap set is also required even if it must be designed and built. Nearly all the difficulties encountered to date relate to the attempt to polish plated nickel with inherent defects. This is not to undermine the vendors but to express concern for attempting to process such a large and heavy piece in a process designed for smaller pieces.

TABLE 2

Materials Used:

Polishing Pads	Buehler Chemsmet 41 Waukegan Road Lake Bluff, IL 60044
Polishing Compounds	
Baikalox Alpha Type Premix 1.0 -.05 μm	Baikowski International Corp. 6006-B Old Pineville Road Charlotte, NC 28217
Buehler .05 μm	Buehler Chemsmet 41 Waukegan Road Lake Bluff, IL 60044
Polyurethane D-65 Shore Hardness .030 in. thick UNFILLED	James H. Rhodes & Co. Route 12-B Franklin Springs, NJ 18841
Polyurethane D-65 Shore Hardness	Hardman Inc. 600 Cortlandt Street Belleville, NJ 07109
Microgrit 3μm & 5μm Untreated	Micro Abrasive Corp. Westfield, Mass.
Silica Colloidal NALCO 2360	Rodel Corp. 9495 E. San Salvador Dr. Scottsdale, AZ 85258
Webril Wipes 100% Cotton	Veratec, Inc. Graphic Arts Products Walpole, MA 02081

APPENDIX I. Figures:

1. Pourbaix Diagrams for Nickel + Nickel-Phosphorous

2. Measured Surface Profile Superimposed on Initial Data

3. Surface Finish - Polish 2; November 1991

a) Diamond Stylus 2 mm scan, Waviness Apparent;

Ra	=	0.210 μm
RMS	=	0.274 μm
Peak to Valley	=	1.789 μm
Waviness	=	0.9 μm
Period	=	1.0 mm

b) Diamond Stylus 0.2mm Scan

Peak to Valley = 0.514 μm

c) Ruby Stylus 31.8mm Scan

Peak to Valley Convex Fit = 0.195 μm

4. Surface Finish - Polish 3, December 1991

a) Diamond stylus, 2.1 mm scan, Minimal Waviness;

Ra	=	0.034 μm
RMS	=	0.043 μm
Peak to Valley	=	0.249 μm

b) 7.0 mm scan, one wave = 0.879 μm

c) 9.0 mm Scan Unfiltered = 0.813 μm

d) Unfiltered Mode Polish #3 p-p = 1.36 μm

e) Ruby Stylus Polish #3 p-p = 0.112 μm

5. Surtronic Portable Profilometer Data

a) Rippled Area After Additional 1.5 Hr. Lapping

b) Rippled Areas After Additional 8.0 Hrs. Lapping

c) Smooth Area After Additional 8.0 Hrs. Lapping

d) Rippled Area vs Smooth Area After All Lapping

e) Rippled Area vs Smooth Area Continued

6. Analysis of Data;

a) Fourier Transform of November Measured Surface Data (FD)

b) Power Spectrum of November Measured Surface Data (FD)

c) Fourier Transform of January Measured Surface Data (FD)

d) Power Spectrum of January Measured Surface Data (FD)

e) Disturbance During Measurement (Ruby Stylus)

f) Axial Profilometer Motion Disturbance Apparent (Ruby)

g) Disturbance During Measurement (Diamond Stylus)

h) Axial Profilometer Motion Disturbance Apparent (Diamond)

7. Polynomial Suface Contour Fit

a) Original Data Fit to Polynomial

b) Residual Error in Fitted Original Data Polynomial

c) Polynomial Coefficients (Original Data)

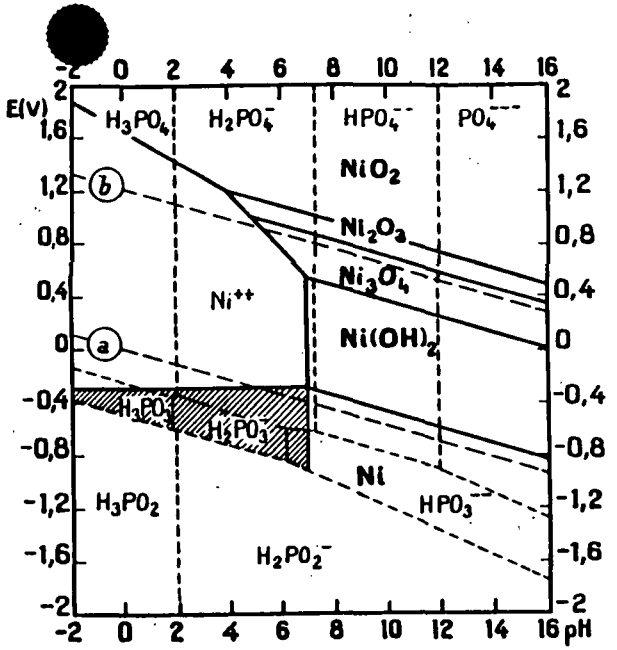
d) Measured Data Fit to Polynomial

d) Residual Error in Fitted Measured Data Polynomial

e) Polynomial Coefficients (Measured Data)

f) Original Data Set (1)

g) Original Data Set (2)



Theoretical conditions for the formation of nickel by the reduction of Ni^{++} ions by hypophosphites. (For solutions containing 0·6 g Ni^{++}/l.)

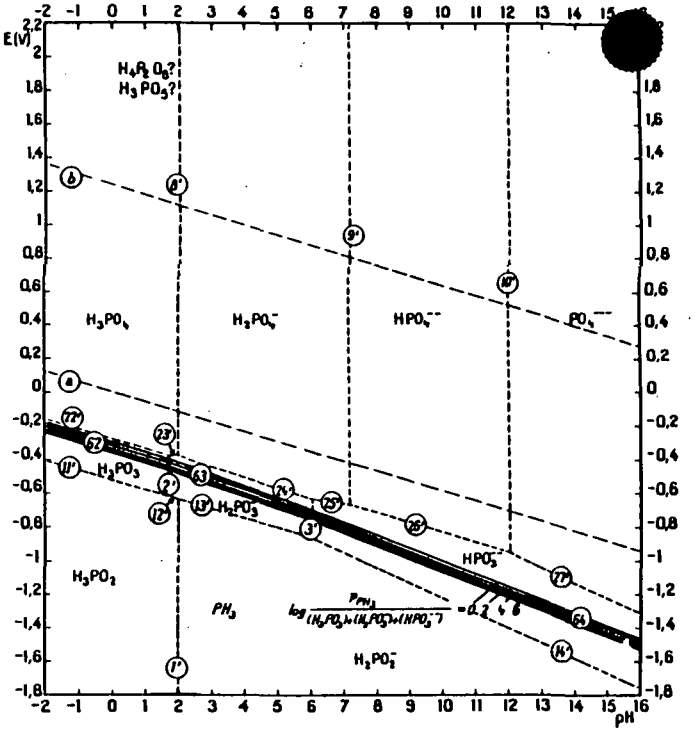
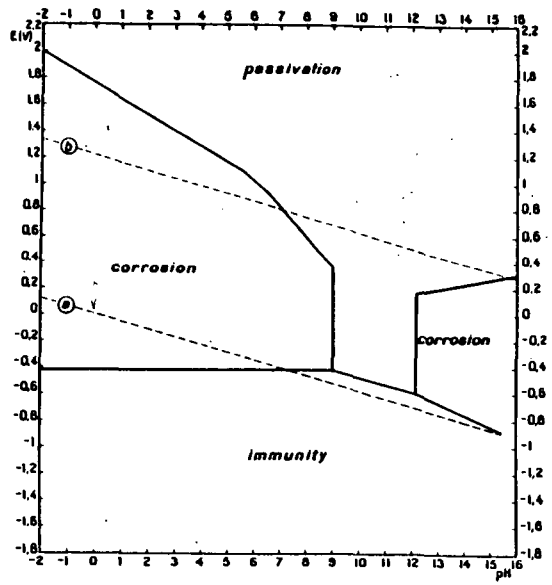
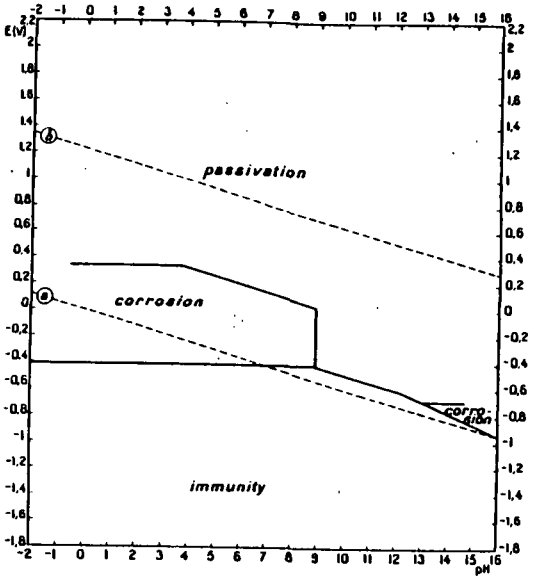


Fig. 1. Potential–pH equilibrium diagram for the system phosphorus–water, at 25°C. (Taking into account the hydrides of phosphorus.)



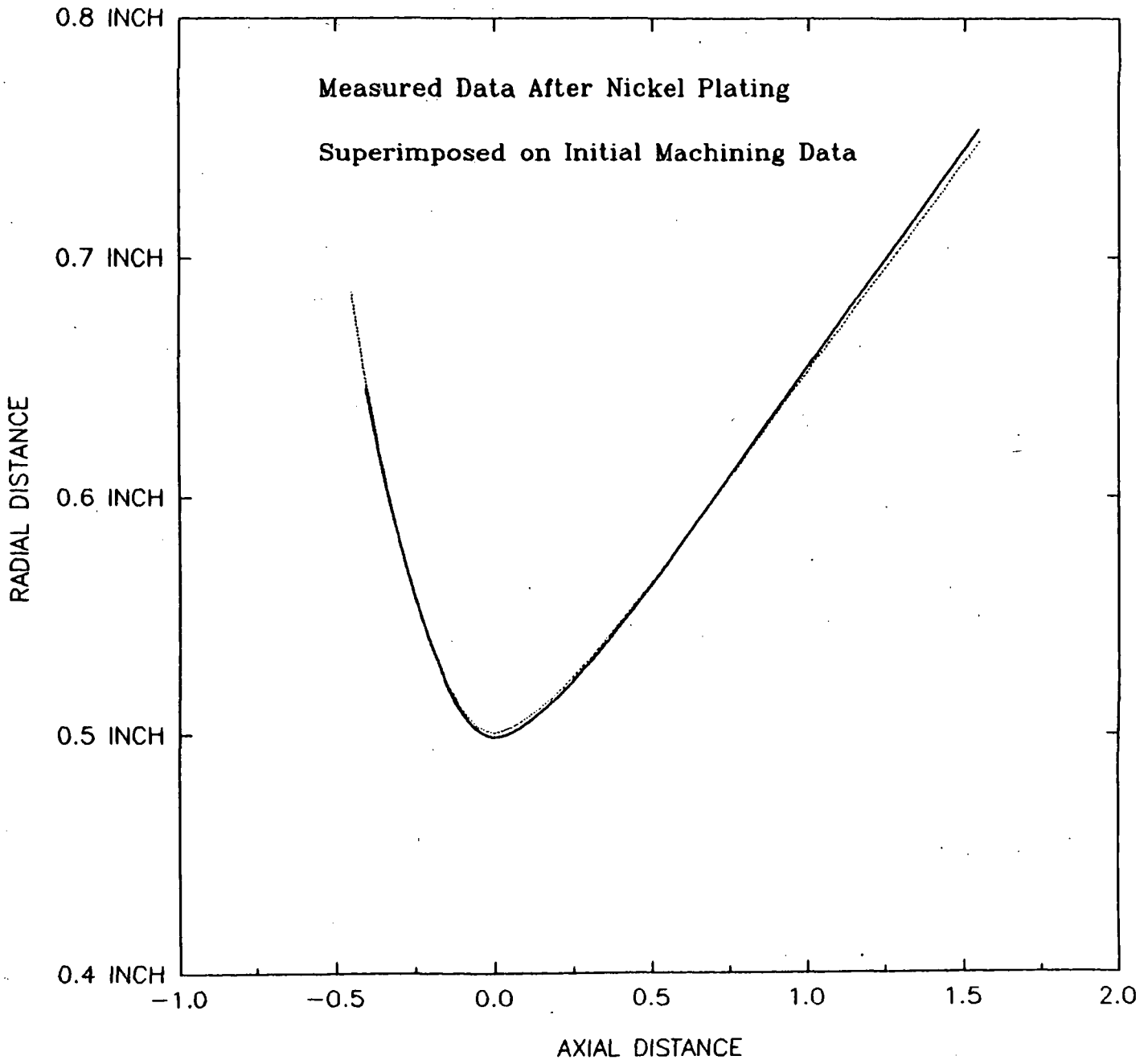
Theoretical domains of corrosion, immunity and passivation of nickel, at 25°C.



Probable experimental conditions of corrosion, immunity and passivation of nickel, in solutions not containing chloride.

Fig. 1 Deposition and Corrosion of Nickel - Phosphorous

MACH 6 WINDTUNNEL NASA LANGLEY RESEARCH CENTER

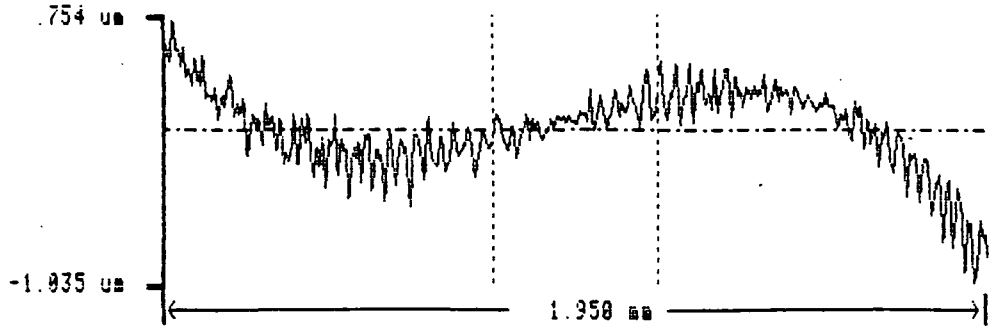


Measured Data
[illegible] to Original
Data

Fig 2a

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude
F6 - Z_Range

Mode	Traverse Length	Reference	Ignore
UNFILTERED	2.0 mm	CONVEX	0 %
NASA NOZZLE FINAL POLISH 1-.002			



Peak To Valley = 1.789 um

TIME: 9: 2
DATE: 22-NOV-91

Taylor-Hobson

F1 - Analysis

Mode	Traverse Length	Reference	Ignore
UNFILTERED	2.0 mm	CONVEX	0 %
NASA NOZZLE FINAL POLISH 1-.002			

Lo	=	1.950 mm	PRa	=	.210 um
PRp	=	.754 um	PRq	=	.274 um
PRv	=	1.035 um	PRsk	=	-.8
PRt	=	1.789 um	PRku	=	4.2
			PDelq	=	1.71 Deg
RADIUS	=	41.531 mm	PLaaq	=	57.710 um
Diameter	=	83.062 mm	PS	=	17.361 um
Z_DATUM	=	-41.472 mm	PSm	=	66.305 um
X_DATUM	=	2.238 mm	PRz	=	.641 um
dZ_DATUM	=	-38.559 mm			
dX_DATUM	=	2.100 mm			

TIME: 9: 2
DATE: 22-NOV-91

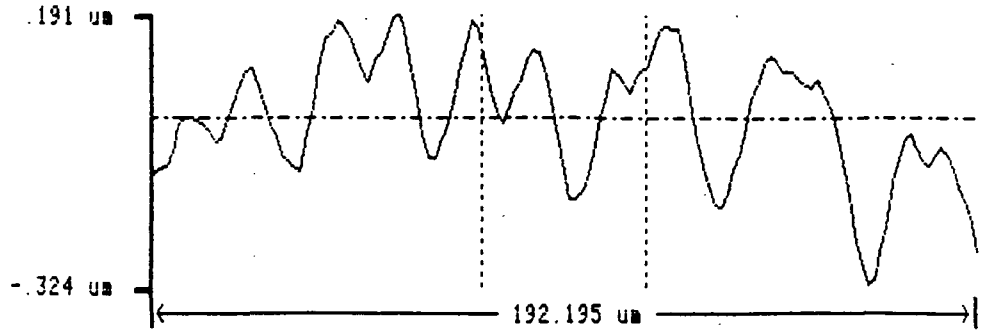
Taylor-Hobson

Diamond Stylus
2 millimeter Travel
Second Polish

Fig 3a

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude
F6 - Z_Range

Mode	Traverse Length	Reference	Ignore
UNFILTERED	.2 mm	STRAIGHT	0 %
NASA NOZZLE FINAL POLISH 1-.002			



Peak To Valley = .514 um

TIME: 4:33
DATE: 12-NOV-91

Taylor-Hobson

F1 - Analysis

Mode	Traverse Length	Reference	Ignore
UNFILTERED	.2 mm	STRAIGHT	0 %
NASA NOZZLE FINAL POLISH 1-.002			

Lo =	192.195 um	PRa =	.095 um
PRp =	.191 um	PRq =	.115 um
PRv =	.324 um	PRsk =	-.5
PRt =	.514 um	PRku =	2.7
		PDelq =	1.54 Deg
SLOPE =	3.01 Deg	PLaaq =	26.803 um
dSLOPE =	-178.36 Deg	PS =	15.931 um
Z_INTERSECT =	-29.775 um	PSm =	26.380 um
X_INTERSECT =	-528.180 um	PRz =	.263 um

TIME: 4:33
DATE: 12-NOV-91

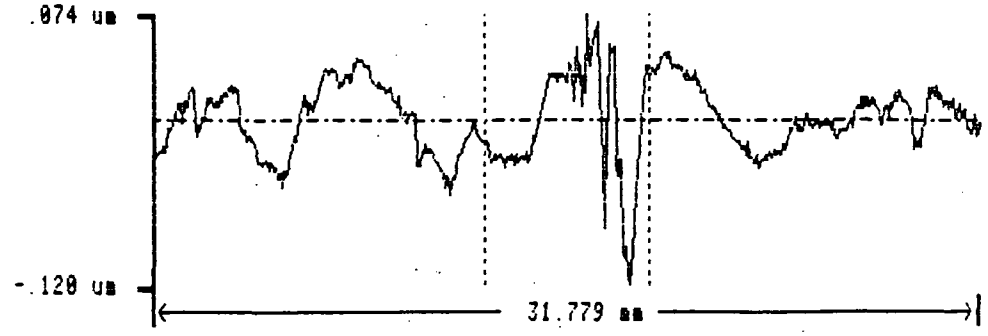
Taylor-Hobson

Diamond Stylus
0.2 mm Travel
Second Polish

3b

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude
F6 - Z_Range

Mode	Traverse Length	Reference	Ignore
UNFILTERED	29.6 mm	CONVEX	0 %
CAU/UAH CAL01-31B 11/12/91			



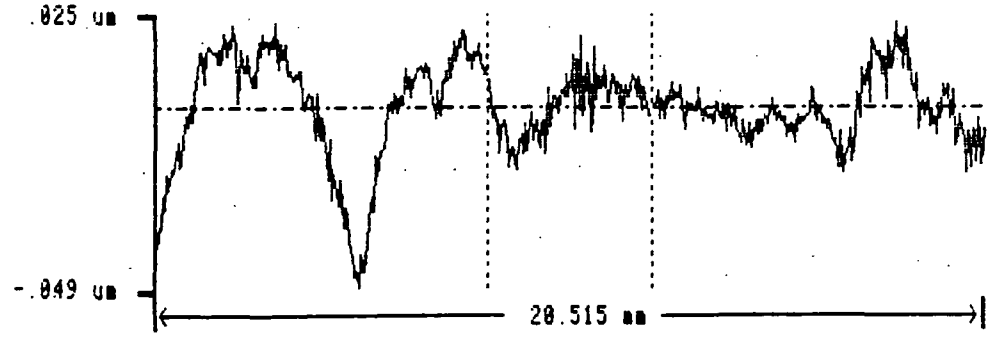
Peak To Valley = .195 um

TIME: 15:51
DATE: 12-NOV-91

Taylor-Hobson

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude
F6 - Z_Range

Mode	Traverse Length	Reference	Ignore
UNFILTERED	19.8 mm	CONVEX	0 %
NASA NOZZLE FINAL POLISH 1 11-12-91			



Peak To Valley = .074 um

TIME: 16:42
DATE: 12-NOV-91

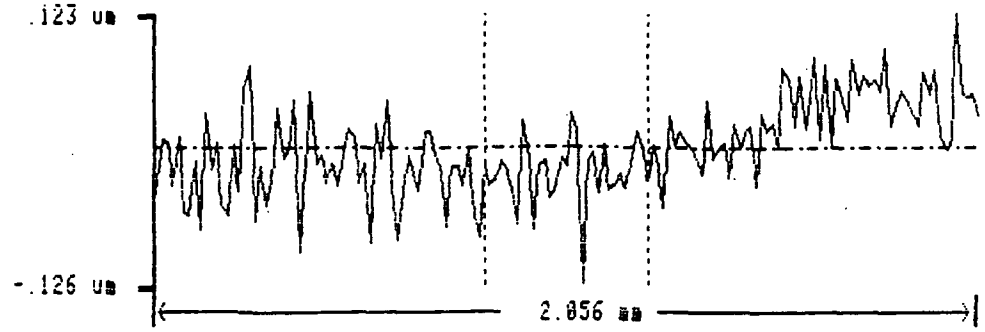
Taylor-Hobson

Ruby Stylus
Data Fit to Convex
Second Polish

Fig 3c

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude
F6 - Z_Range

Mode	Traverse Length	Reference	Ignore
UNFILTERED	2.1 mm	STRAIGHT	0 %
MACH6 3DL REPOLISH 01-07-92			



Peak To Valley = .249 um

TIME: 14:26
DATE: 7-JAN-92

Taylor-Hobson

F1 - Analysis

Mode	Traverse Length	Reference	Ignore
UNFILTERED	2.1 mm	STRAIGHT	0 %
MACH6 3DL REPOLISH 01-07-92			

Lo	=	2.056 mm	PRa	=	.034 um
PRp	=	.123 um	PRq	=	.043 um
PRv	=	.126 um	PRsk	=	.0
PRt	=	.249 um	PRku	=	3.0
			PDelq	=	.16 Deg
SLOPE	=	10.44 Deg	PLamq	=	94.661 um
dSLOPE	=	179.93 Deg	PS	=	37.970 um
Z_INTERSECT	=	-2.385 mm	PSm	=	78.436 um
X_INTERSECT	=	-13.031 mm	PRz	=	.157 um

TIME: 14:26
DATE: 7-JAN-92

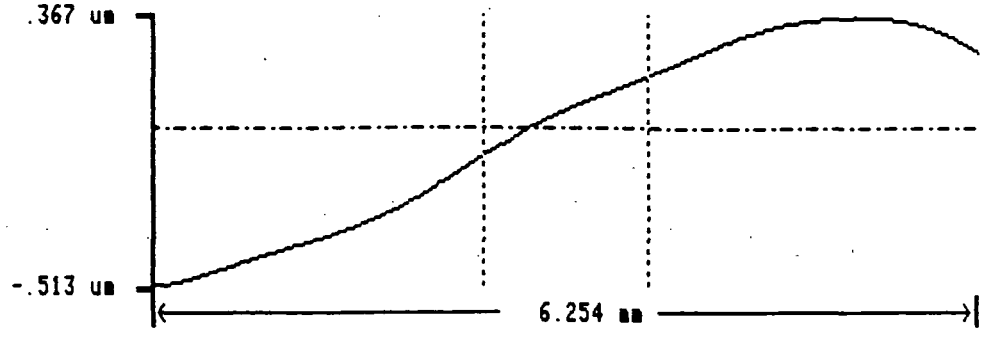
Taylor-Hobson

Diamond Stylus
2.1 mm Scan
Third Polish Jan 92

Fig 4a

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude
F6 - Z_Range

Mode	Cut Off	Filter	Reference	Ignore
WAVINESS	2.50 mm	PC	STRAIGHT	0 %
MACH6 1D REPOLISH 01-07-92				



Peak To Valley = .879 um

TIME: 16:28
DATE: 7-JAN-92

Taylor-Hobson

F1 - Analysis

Mode	Cut Off	Filter	Reference	Ignore
WAVINESS	2.50 mm	PC	STRAIGHT	0 %
MACH6 1D REPOLISH 01-07-92				

WRtm	= .431 um	Lo	= 6.254 mm	WRa	= .275 um
WRpm	= .127 um	WRp	= .367 um	WRq	= .304 um
WRy	= .447 um	WRv	= .513 um	WRsk	= -.3
WRt1	= .415 um	WRt	= .879 um	WRku	= 1.5
WRt2	= .447 um			WDelq	= .01 Deg
		SLOPE	= 10.34 Deg	WLamq	= 15.608 mm
		dSLOPE	= -179.99 Deg	WS	= .000 um
		Z_INTERSECT	= -1.018 mm	WSm	= .000 um
		X_INTERSECT	= -5.570 mm		

TIME: 16:28
DATE: 7-JAN-92

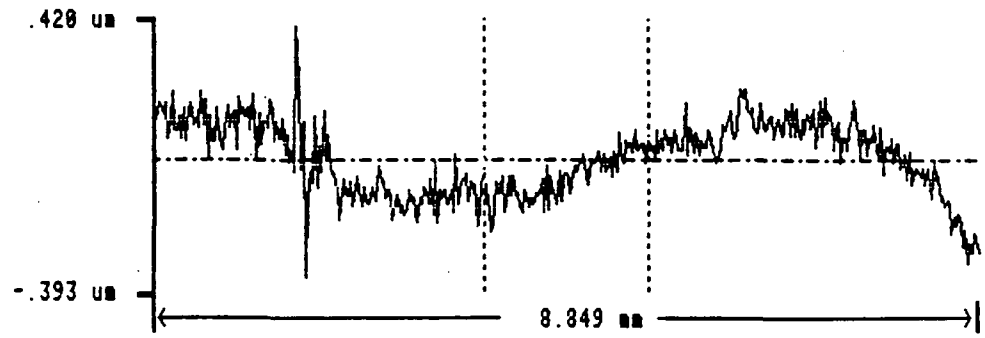
Taylor-Hobson

Diamond Stylus
Waviness Mode Polish #3

Fig 4b

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude
F6 - Z_Range

Mode	Traverse Length	Reference	Ignore
UNFILTERED	9.0 mm	STRAIGHT	0 %
MACH6 1D REPOLISH 01-07-92			



Peak To Valley = .813 um

TIME: 16:32
DATE: 7-JAN-92

Taylor-Hobson

F1 - Analysis

Mode	Traverse Length	Reference	Ignore
UNFILTERED	9.0 mm	STRAIGHT	0 %
MACH6 1D REPOLISH 01-07-92			

Lo	=	8.849 mm	PRa	=	.099 um
PRp	=	.420 um	PRq	=	.115 um
PRv	=	.393 um	PRsk	=	-.2
PRt	=	.813 um	PRku	=	2.5
			PDelq	=	.50 Deg
SLOPE	=	10.35 Deg	PLamq	=	82.943 um
dSLOPE	=	180.00 Deg	PS	=	23.367 um
Z_INTERSECT	=	-1.076 mm	PSm	=	133.294 um
X_INTERSECT	=	-5.887 mm	PRz	=	.617 um

TIME: 16:32
DATE: 7-JAN-92

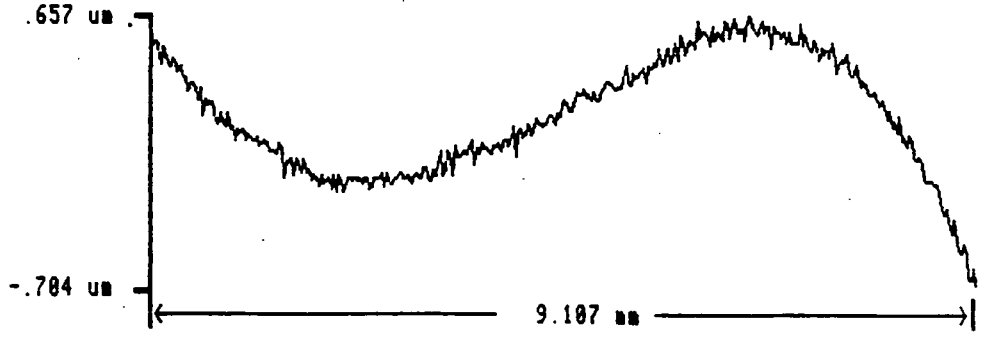
Taylor-Hobson

Fig 4c

Diamond Stylus
9 mm Scan
Polish #3

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Contract
F5 - Invalid
F6 - Z_Range

Mode	Traverse Length	Reference	Ignore
UNFILTERED	10.4 mm	STRAIGHT	0 %
MACH6 3DL REPOLISH 01-07-92			



Peak To Valley = 1.361 um

TIME: 14:35
DATE: 7-JAN-92

Taylor-Hobson

F1 - Analysis

Mode	Traverse Length	Reference	Ignore
UNFILTERED	10.6 mm	STRAIGHT	0 %
MACH6 3DL REPOLISH 01-07-92			

Lo	=	10.410 mm	PRa	=	1.286 um
PRp	=	1.829 um	PRq	=	1.554 um
PRv	=	4.272 um	PRsk	=	-.8
PRt	=	6.101 um	PRku	=	2.9
			PDelq	=	.17 Deg
SLOPE	=	10.40 Deg	PLamq	=	3.252 mm
dSLOPE	=	180.00 Deg	PS	=	150.845 um
Z_INTERSECT	=	******** mm	PSm	=	7.834 mm
X_INTERSECT	=	******** mm	PRz	=	.000 um

TIME: 11:35
DATE: 7-JAN-92

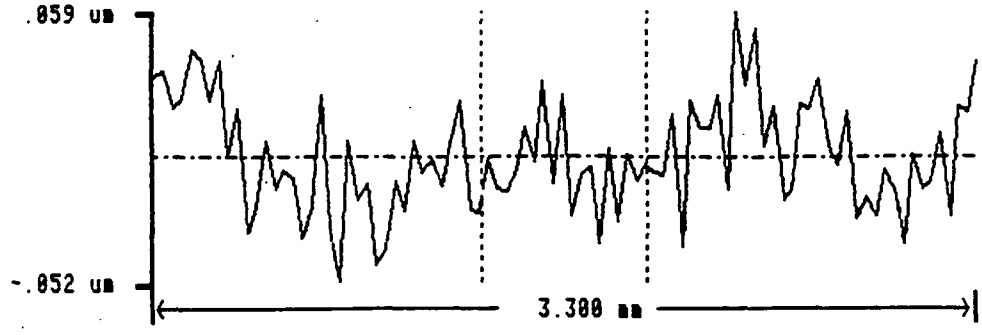
Taylor-Hobson

Diamond Stylus
10 mm Scan Polish #3

Fig 4d

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude
F6 - Z_Range

Mode	Traverse Length	Reference	Ignore
UNFILTERED	3.3 mm	STRAIGHT	0 %
MACH6 1R REPOLISH 01-07-92			



Peak To Valley = .112 um

TIME: 11: 1
DATE: 7-JAN-92

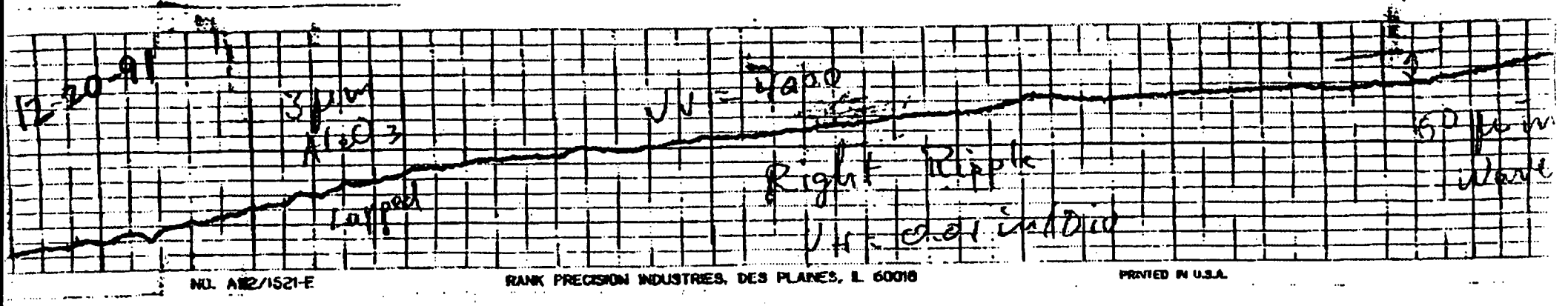
-1-

Taylor-Hobson

Fig 4e

Ruby Stylus
3.3 mm Scan

Polish #3



Right "Rippled" side After an Additional

1.5 Hours Polishing with 5 μm Compound

Followed by 1.0 Hours with 3 μm Compound

Vertical = 25 μinch/Div

Horizontal = 0.01 inch/Div

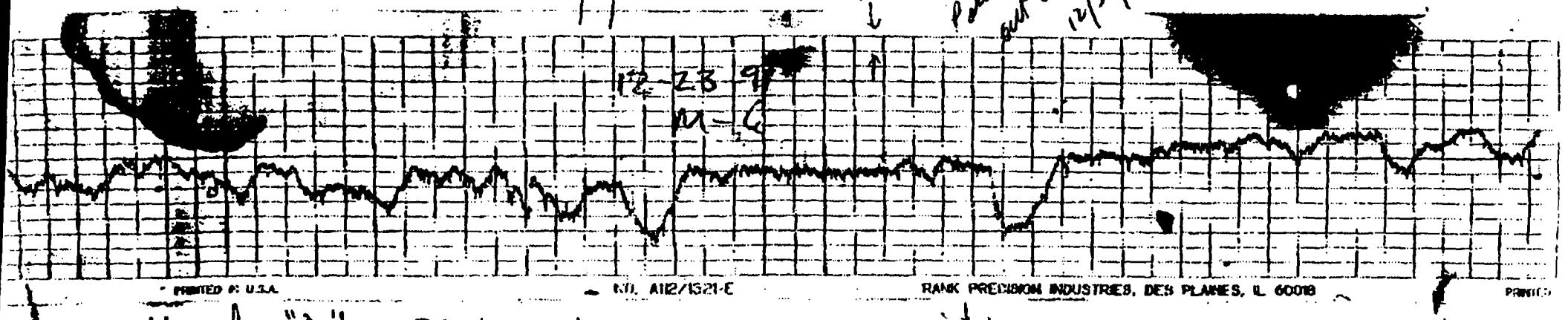
Total Span CA 0.5 inch

Rippled Area 12-20-91

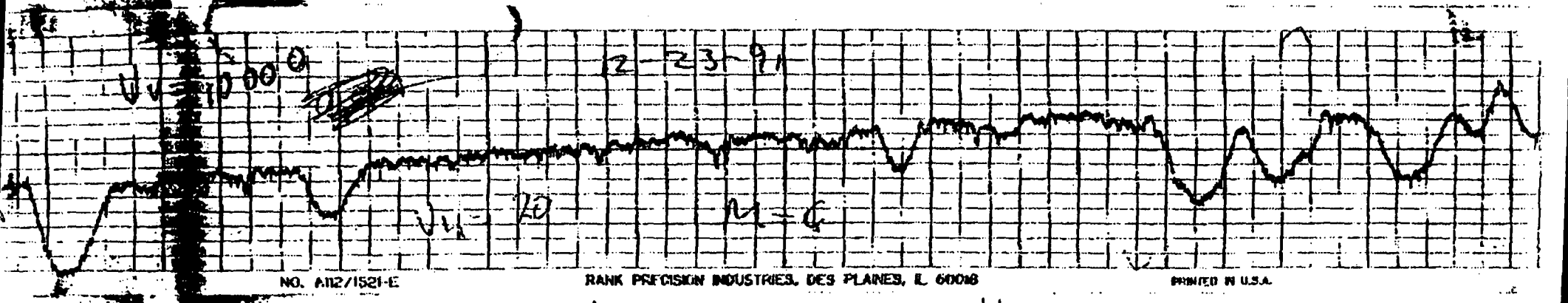
1.5 Hours Lapping

Polish #2

Fig 5a



Right Side "A" Eight Hours Lapping with 3μm Compound



Left Side "B" Eight Hours Lapping with 3μm Compound

Vertical Scale = 10μinch/Div Horiz. = 0.01 inch/Div

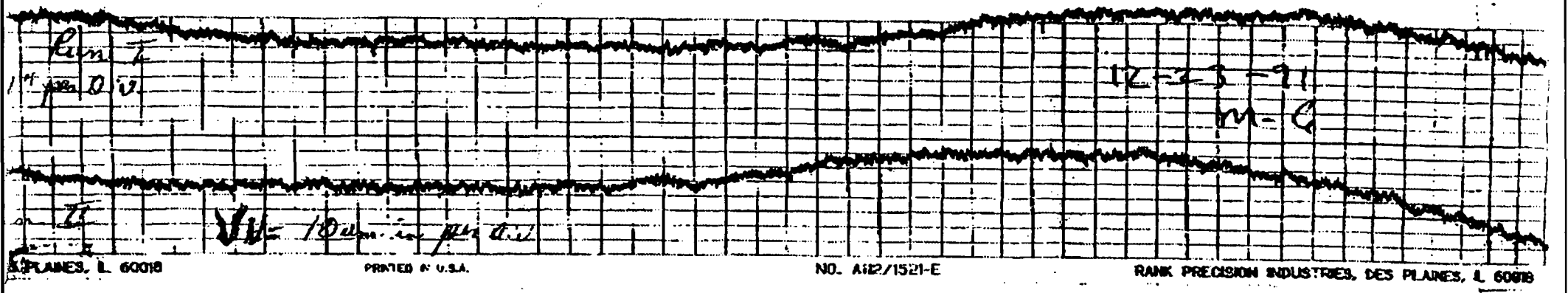
Total Lapping Time Exceeds 12 Hours

Including 1μm Polishing Compound

+1 [illegible] pA 0.5 inch

Fig 5b1 9.5

12-27-91



Smooth Area Eight Hours Lapping 3 µm compound

Vertical = 10 µ inch / Div

Horizontal = 0.01 inch / Div

Total Span CA 0.5 inch

Note: About 4.0 hours additional lapping beyond visit at this point –

12-23-91

Fig 5 b2 9.5 Hours
T.I.I Pre-Polish #3

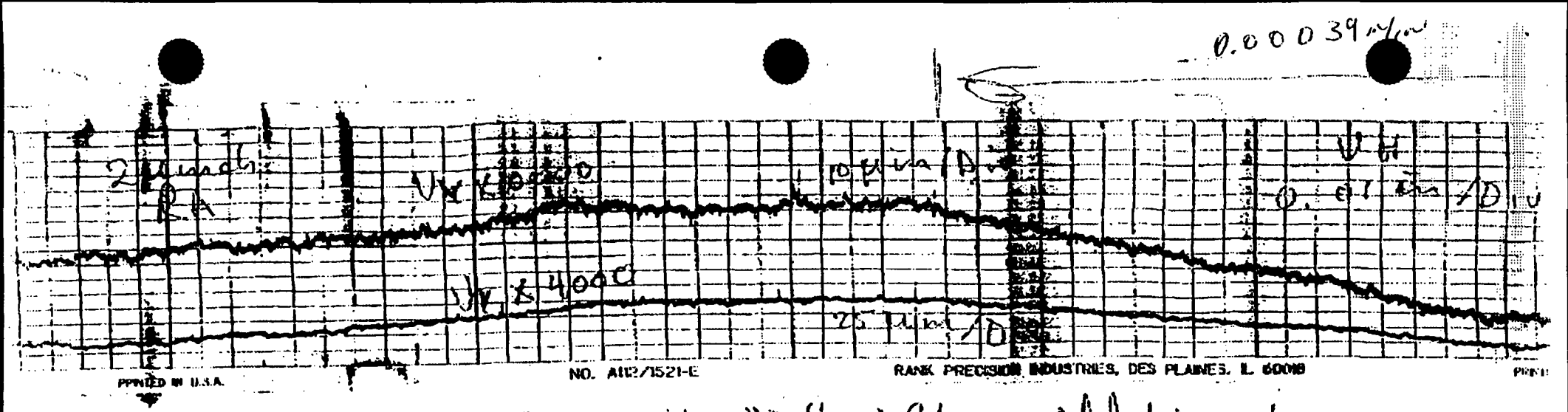
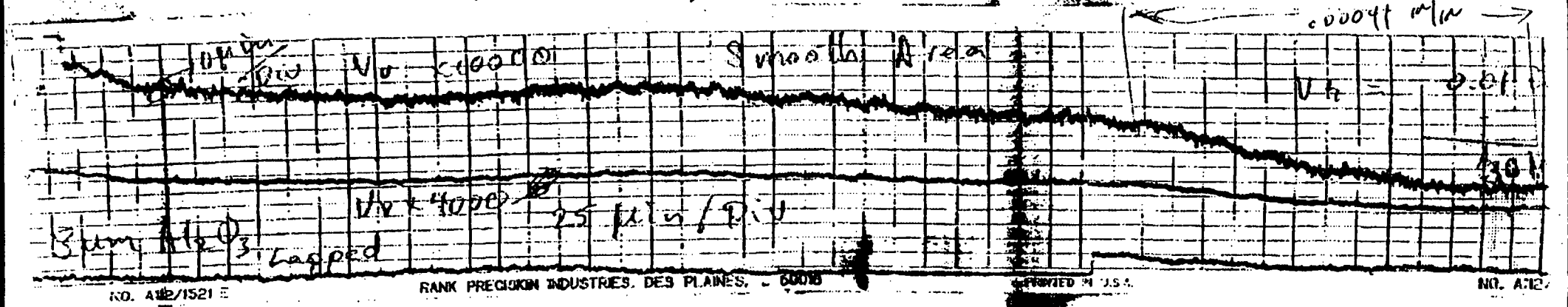


Fig 5c

Left Side "B" After Additional
1.5 Hours Polishing with 5µm Compound
Followed by 1.0 Hours with 3µm Compound



"Smooth Area"

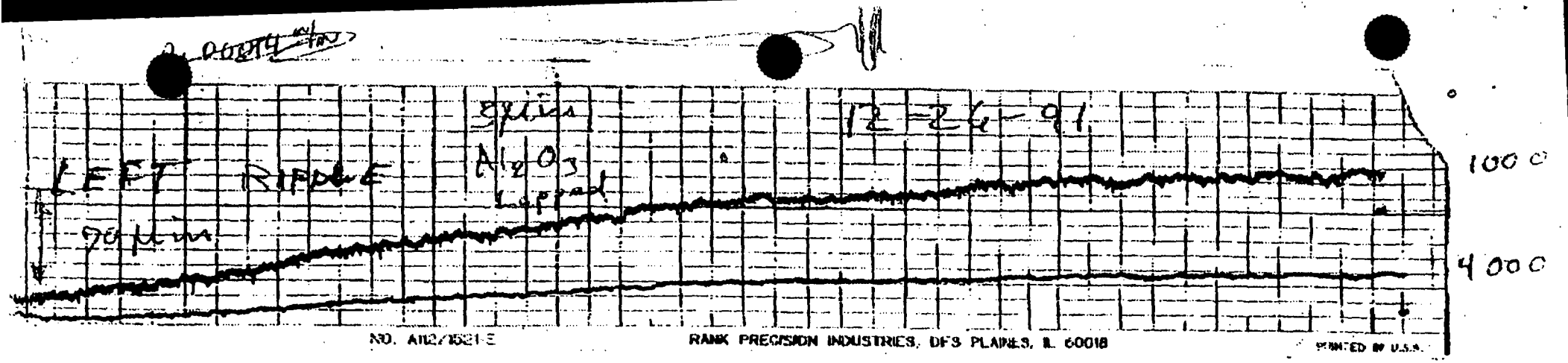
Comparison of
Rippled vs Smooth
Area all Hours

Same as Above

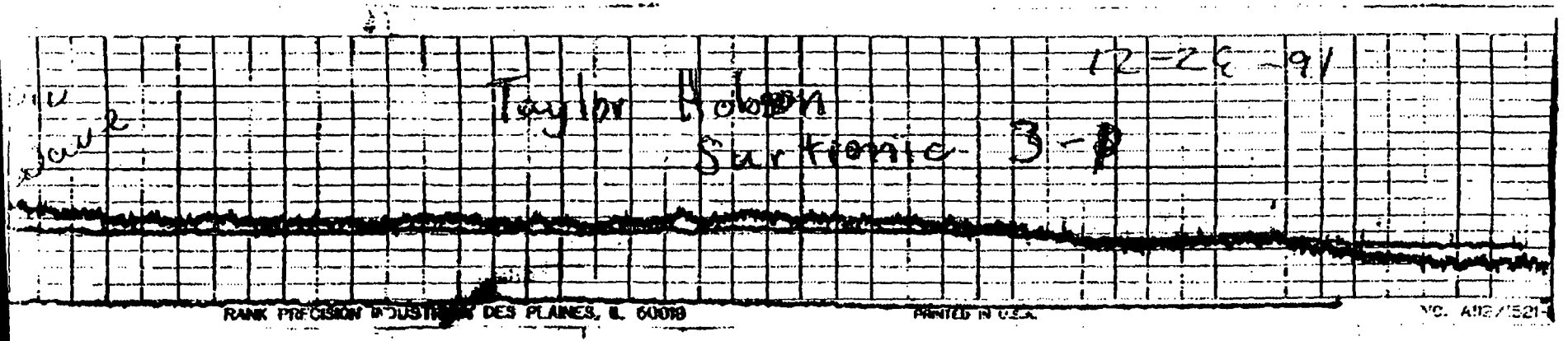
Total Span CA 1 inch

12-26-91

Fig 5d



5 c cont.



5d cont.

11 Hours
Re Polish

12-26-91

$m := 10$

$L := 2^m$

$j := 0 \,..\, L - 1$

$A := READPRN(M)$

$\sigma_j := A_{j+1} - A_j$

CALL "FILENAME M" FROM COMMAND:

SELECT DRIVE:FILE.PRN

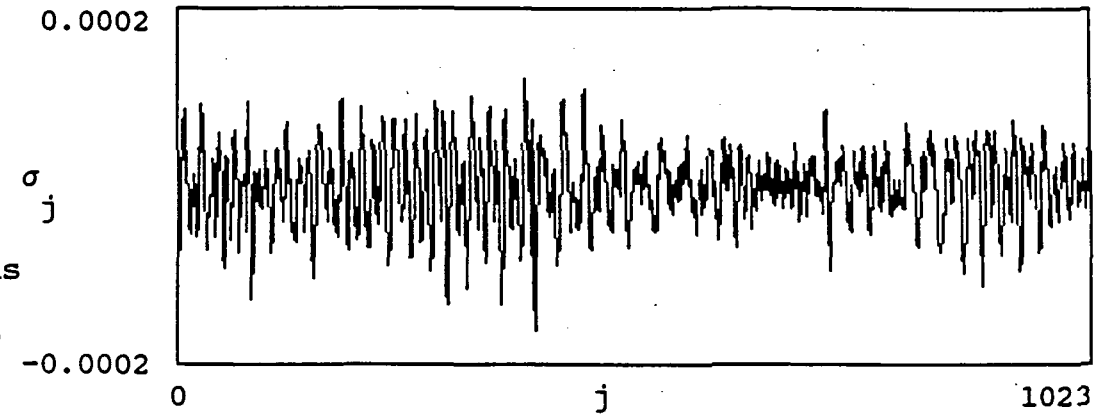
SET UP A VECTOR OF INTERVALS

j MUST = 2^m WITH m A WHOLE NO.

RE-ENTER 'A' AFTER SELECTING FILE

REMOVE TILT BY FORWARD DIFFERENCE

ROUGHNESS DATA



MECHANICALLY POLISHED
1024 POINTS σ_j

Diamond Stylus

Millimeters

2 Millimeter Scan

$f := fft(\sigma)$

$k := 0 \,..\, 2^{m-1}$

FOURIER TRANSFORM

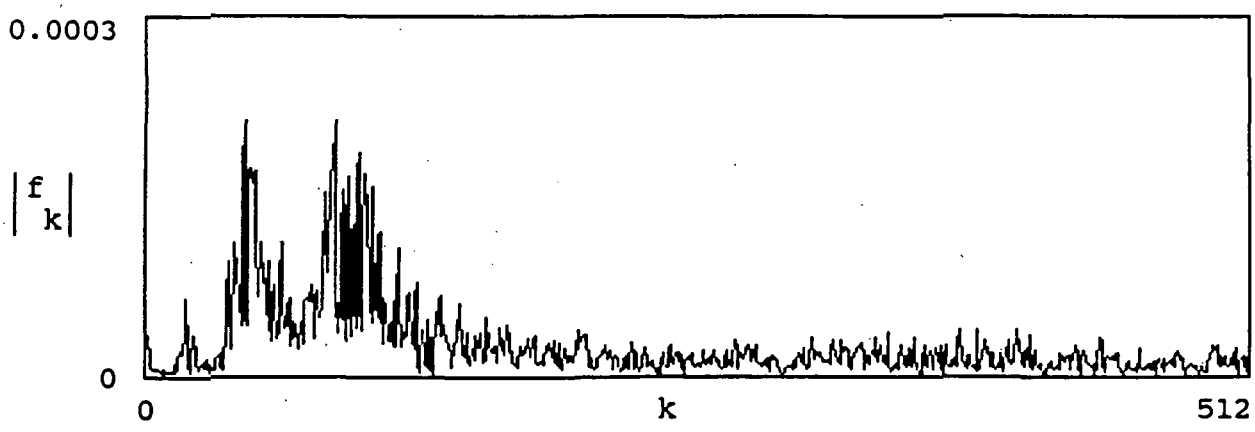


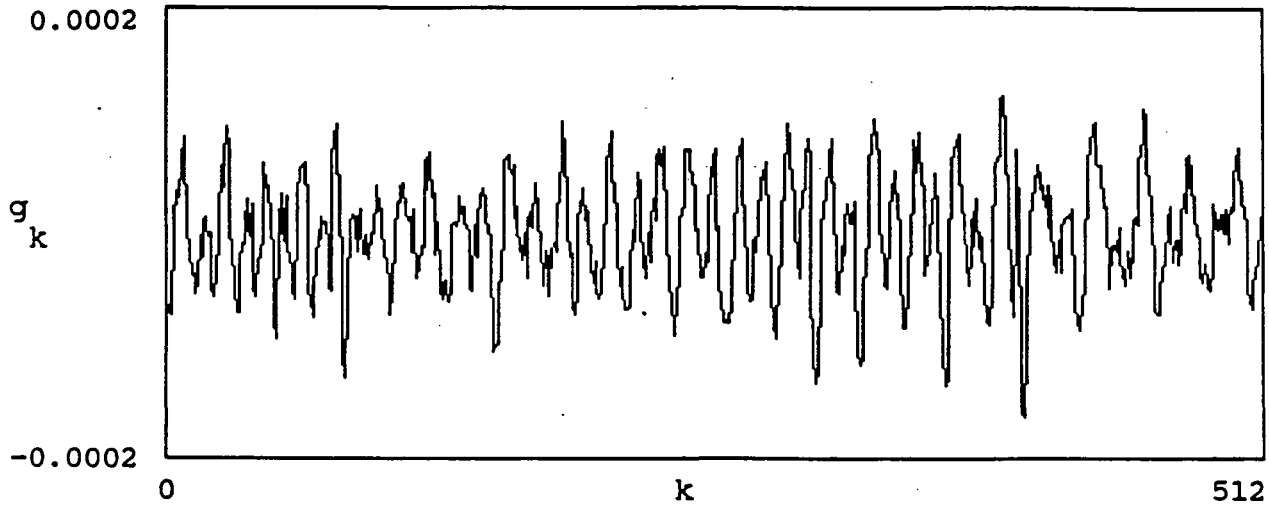
Fig. 6a

Frequency Analysis of Polishing Data
Second Polish - Note Frequency Content

$g := ifft(f)$

$k := 0 \,..\, 2^{m-1}$

INVERSE TRANSFORM
ORIGINAL SPECTRUM



$b := 0 \,..\, 2^{m-1} - 1$

$y_b := f_b \cdot f_b$

POWER SPECTRUM

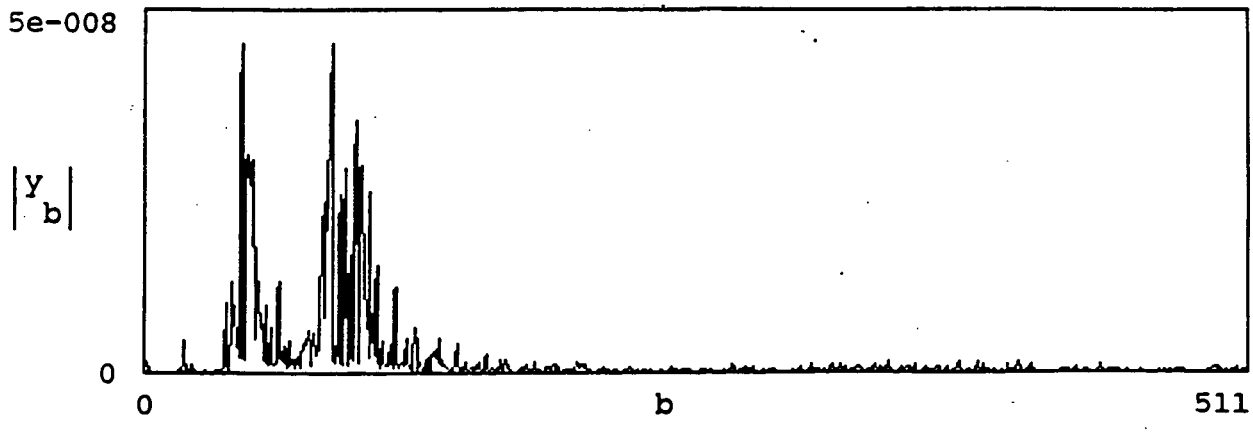
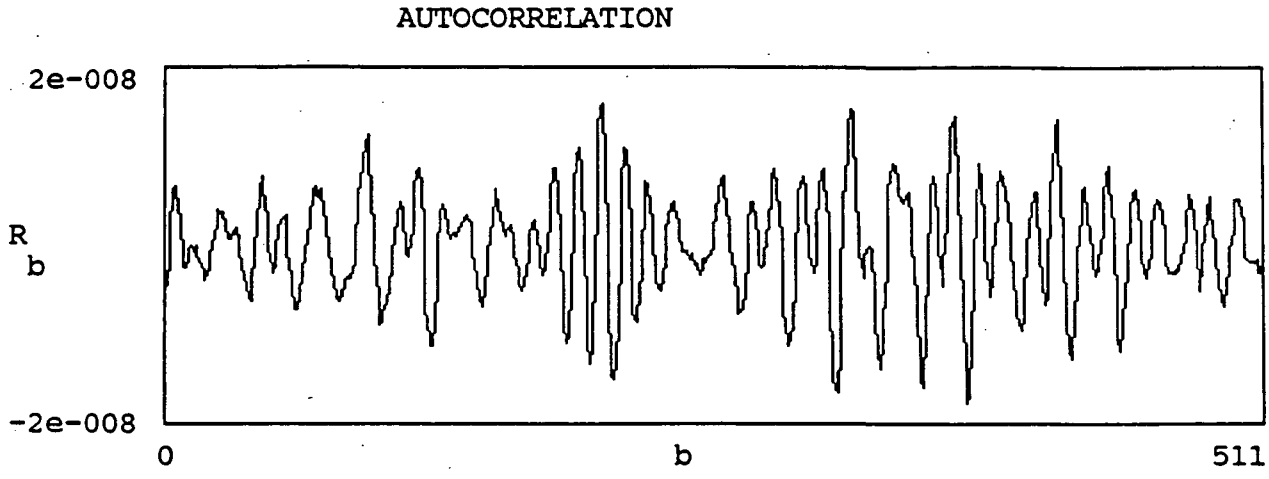


Fig 6b1

$$q_{b+1} := \left[f_{b+1}\right] \cdot \left[f_{b+1}\right]$$

R := ifft(q)



Y := icfft(y)

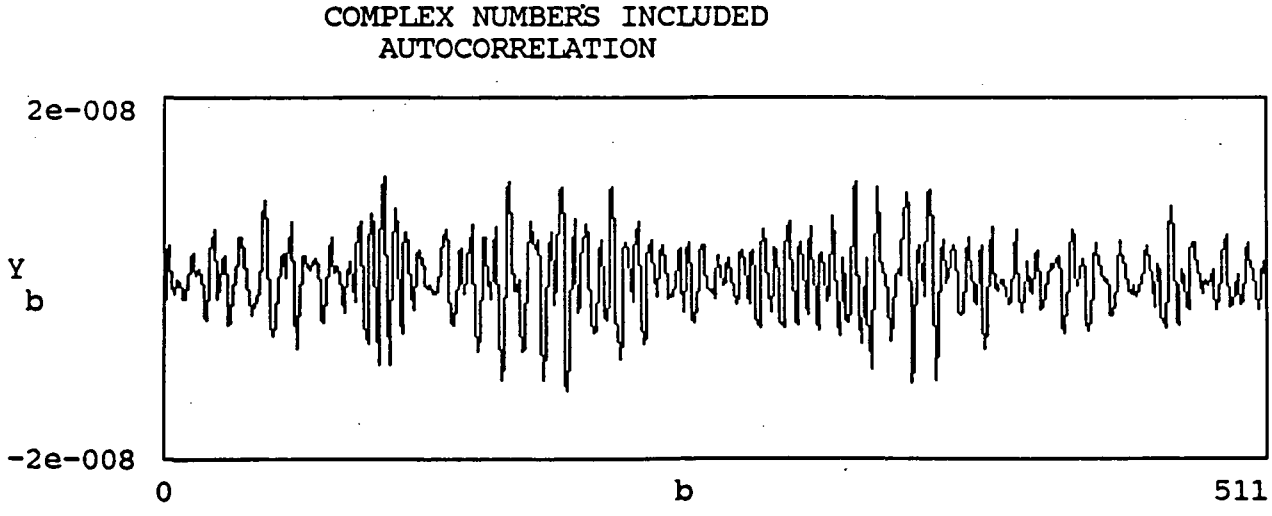


Fig 6.62

$m := 9$

$L := 2^m$

$j := 0 \ldots L - 1$

$A := READPRN(M)$

$\sigma_j := A_{j+1} - A_j$

CALL "FILENAME M" FROM COMMAND:

SELECT DRIVE:FILE.PRN

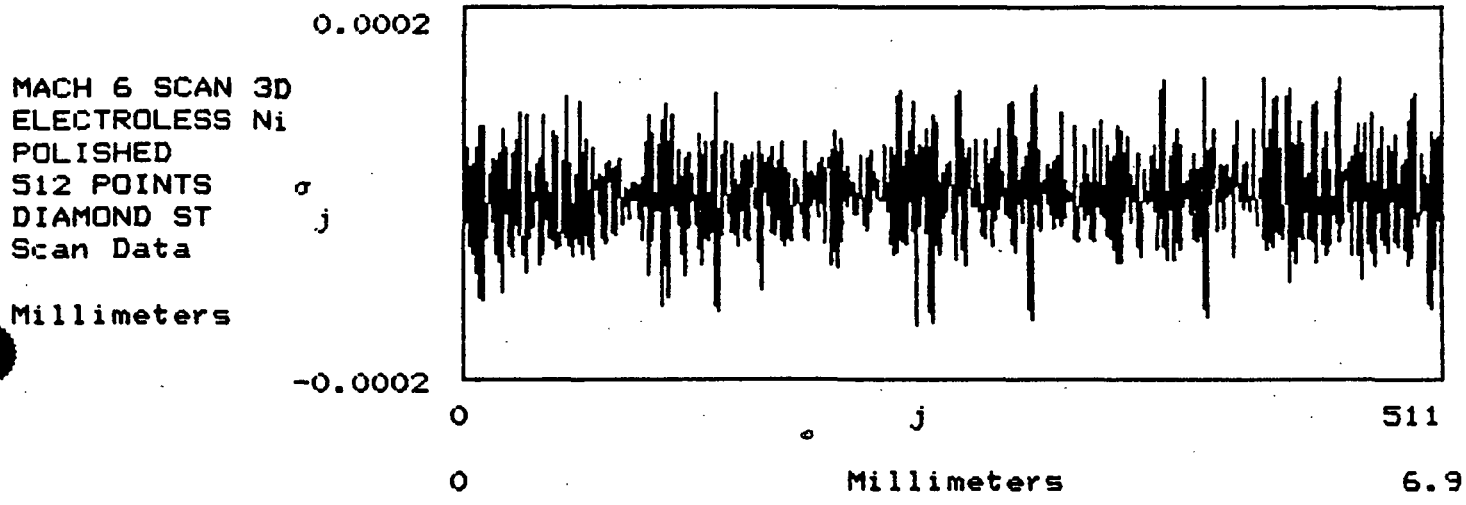
SET UP A VECTOR OF INTERVALS

j MUST = 2^m WITH m A WHOLE NO.

RE-ENTER 'A' AFTER SELECTING FILE

REMOVE TILT BY FORWARD DIFFERENCE

ROUGHNESS DATA



$f := fft(\sigma)$

$k := 0 \ldots 2^{m-1}$

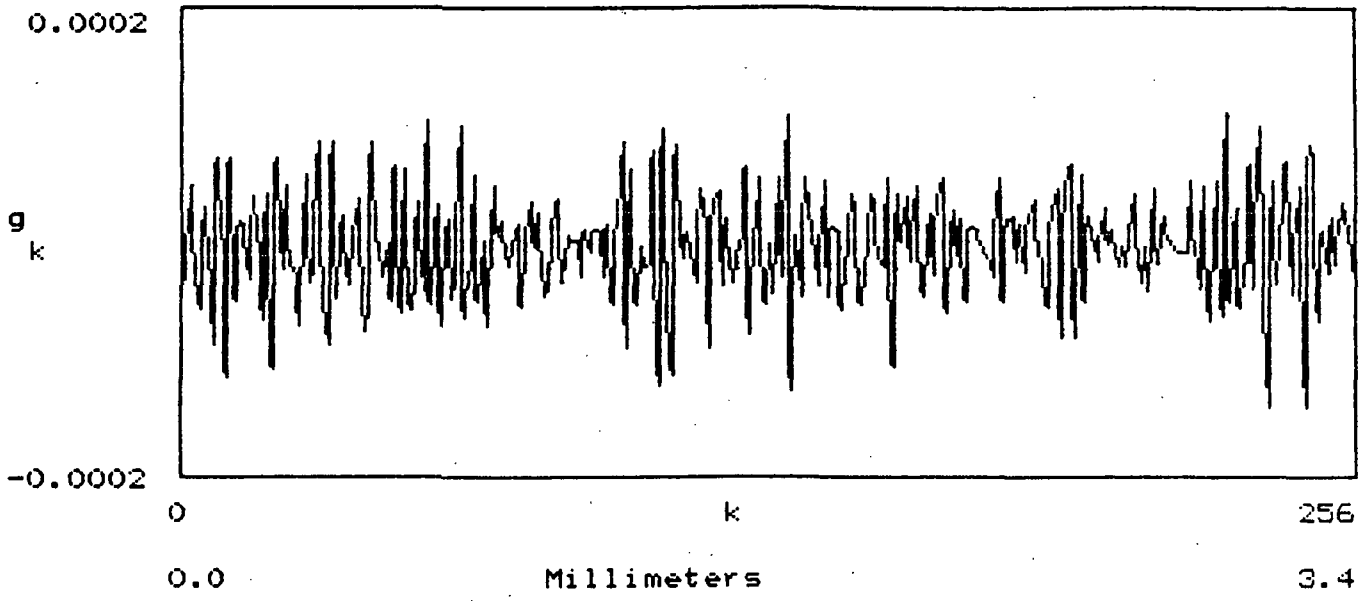
FOURIER TRANSFORM

Fig 6C Frequency Analysis of Polishing Data
Third Polish - Note smoother Freq. Spectrum

$g := ifft(f)$

$k := 0 \,..\, 2^{m-1}$

INVERSE TRANSFORM
ORIGINAL SPECTRUM



$b := 0 \,..\, 2^{m-1} - 1$

$y_b := f_b \cdot f_b$

POWER SPECTRUM

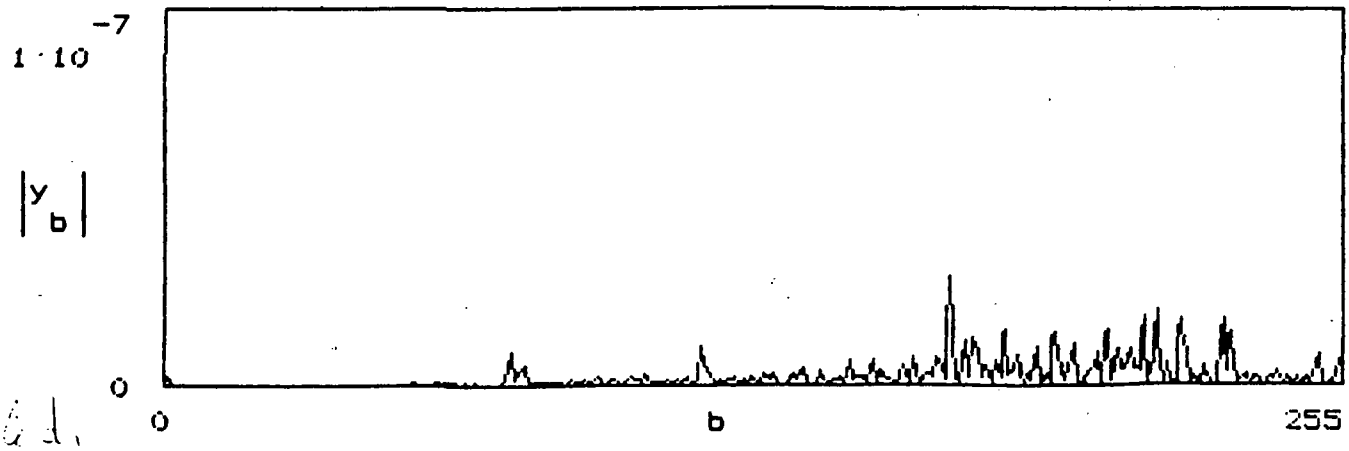
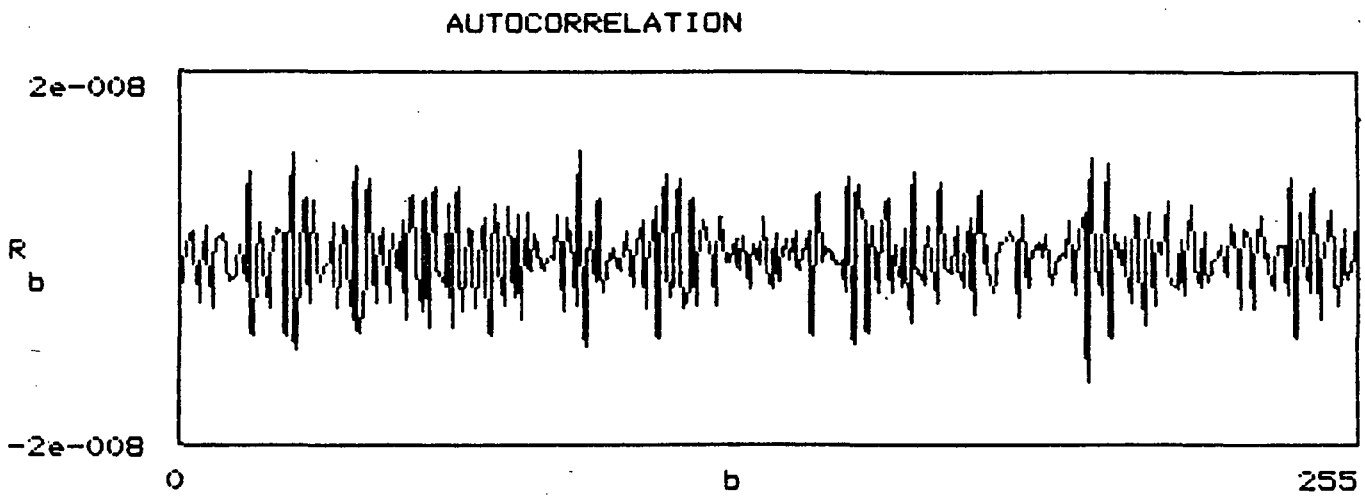


Fig 6d.

$$q_{b+1} := \left[f_{b+1}\right] \cdot \left[f_{b+1}\right]$$

R := ifft(q)



Y := icfft(y)

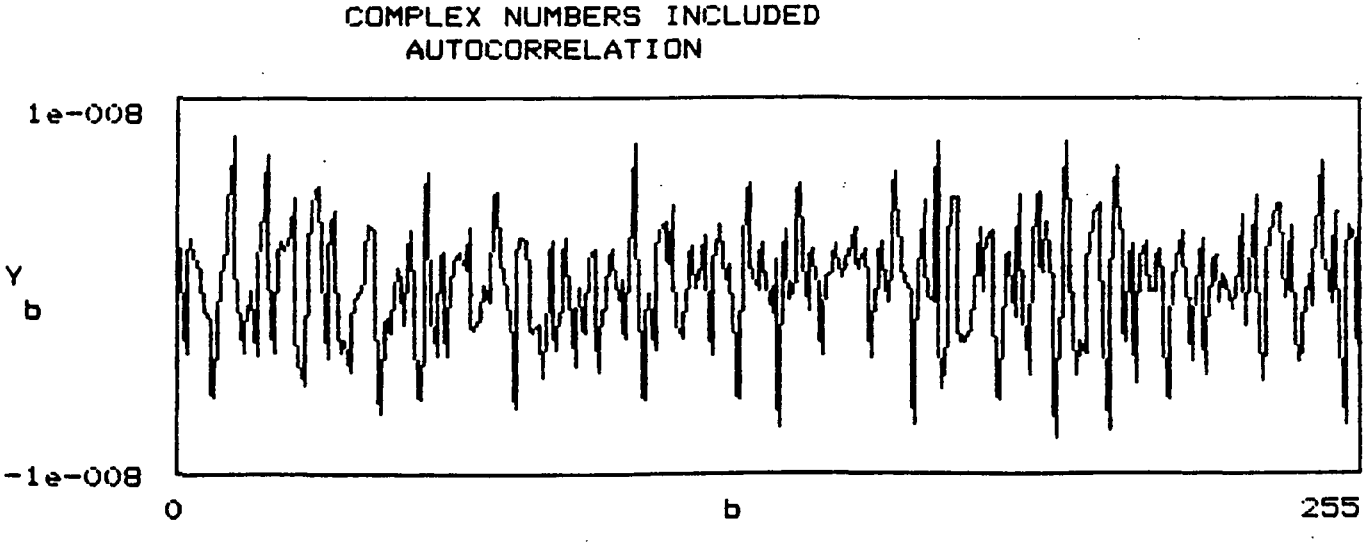


Fig 6 of 12.

$m := 10$

$L := 2^m$

$j := 0 \,..\, L - 1$

$A := READPRN(M)$

$\sigma_j := A_{j+1} - A_j$

CALL "FILENAME M" FROM COMMAND:

SELECT DRIVE:FILE.PRN

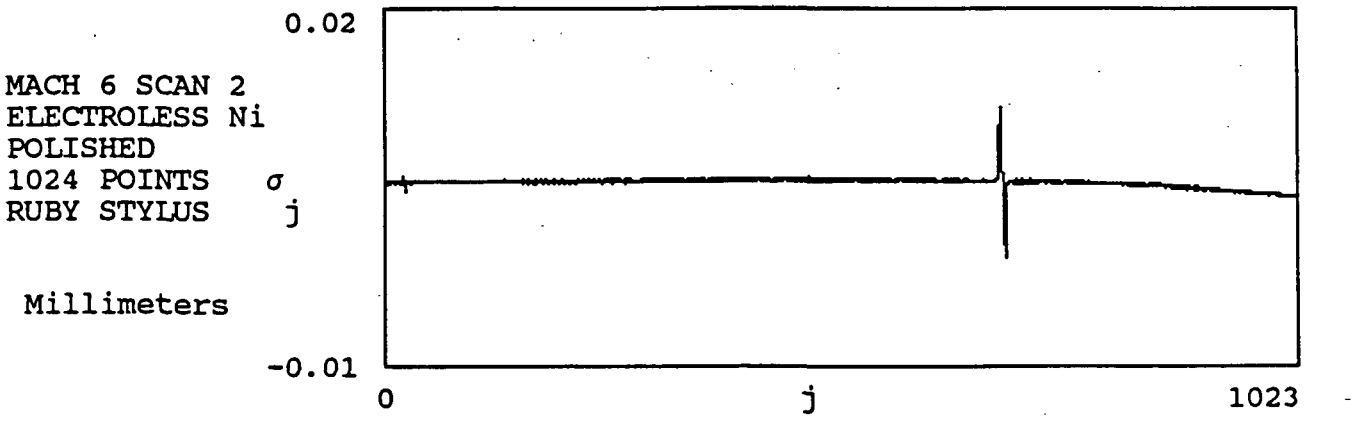
SET UP A VECTOR OF INTERVALS

j MUST = 2^m WITH m A WHOLE NO.

RE-ENTER 'A' AFTER SELECTING FILE

REMOVE TILT BY FORWARD DIFFERENCE

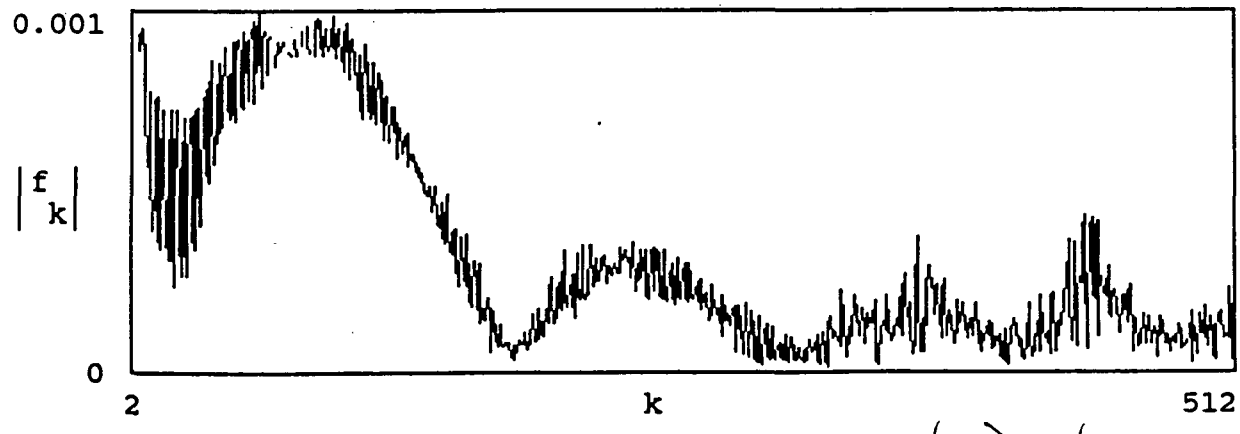
ROUGHNESS DATA



$f := fft(\sigma)$

$k := 0 \,..\, 2^{m-1}$

FOURIER TRANSFORM



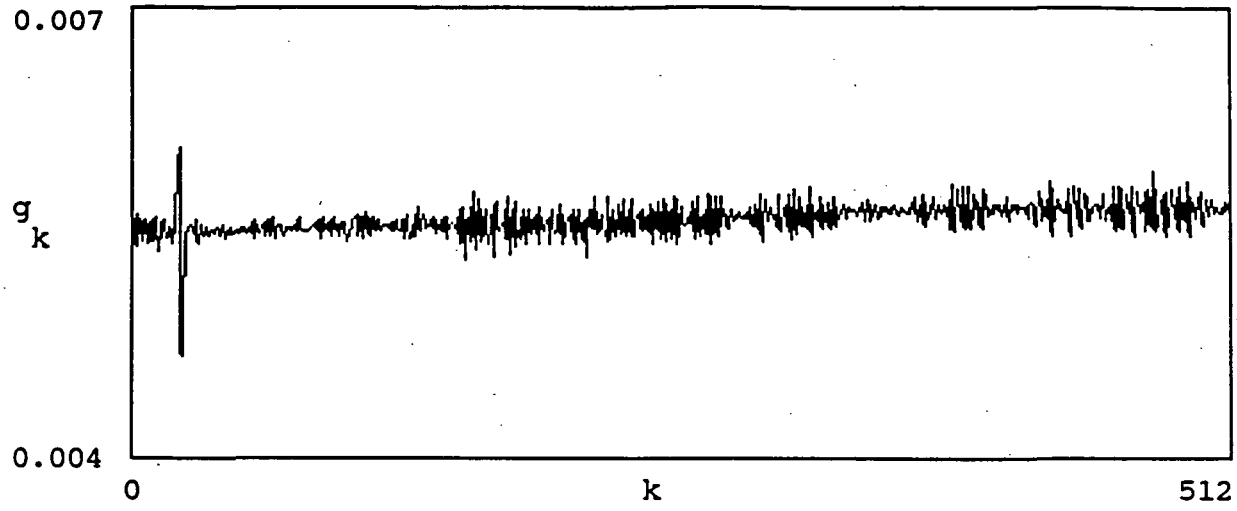
Analysis of Measured Disturbance
Note two spikes due to
disturbance (Ruby Stylus) (Second

Fig 6e1

$g := ifft(f)$

$k := 0 \,..\, 2^{m-1}$

INVERSE TRANSFORM
ORIGINAL SPECTRUM



$b := 0 \,..\, 2^{m-1} - 1$

$y_b := f_b \cdot f_b$

POWER SPECTRUM

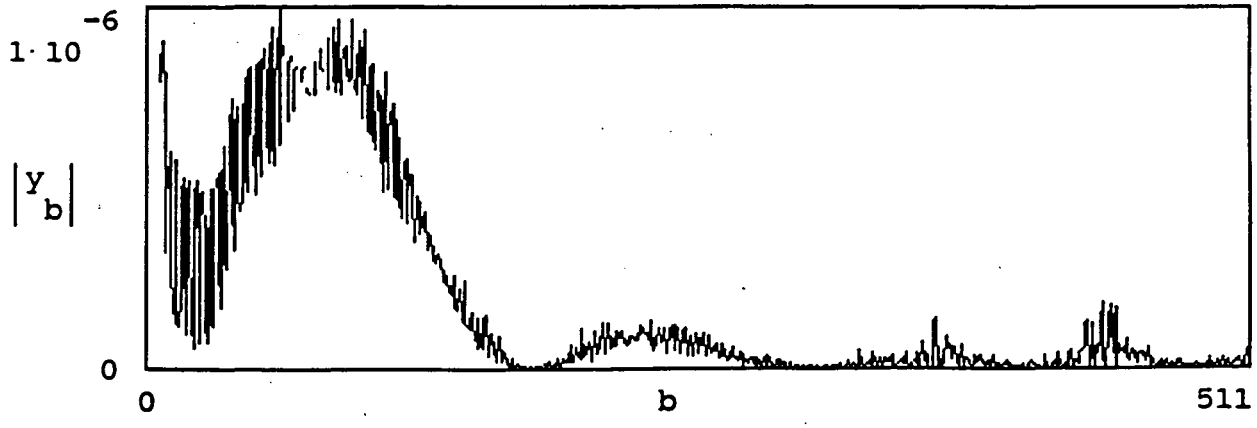
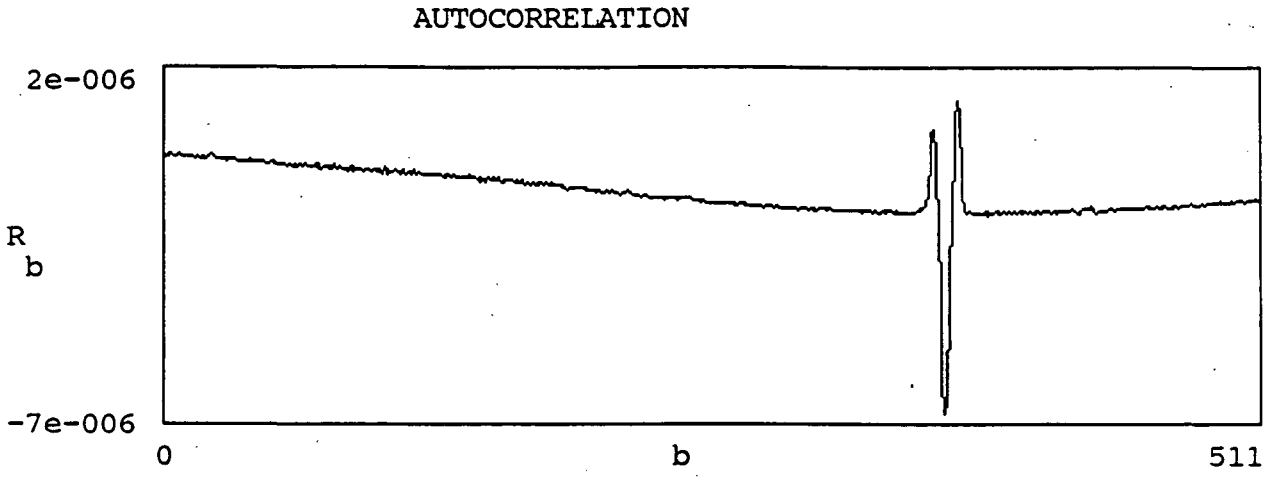


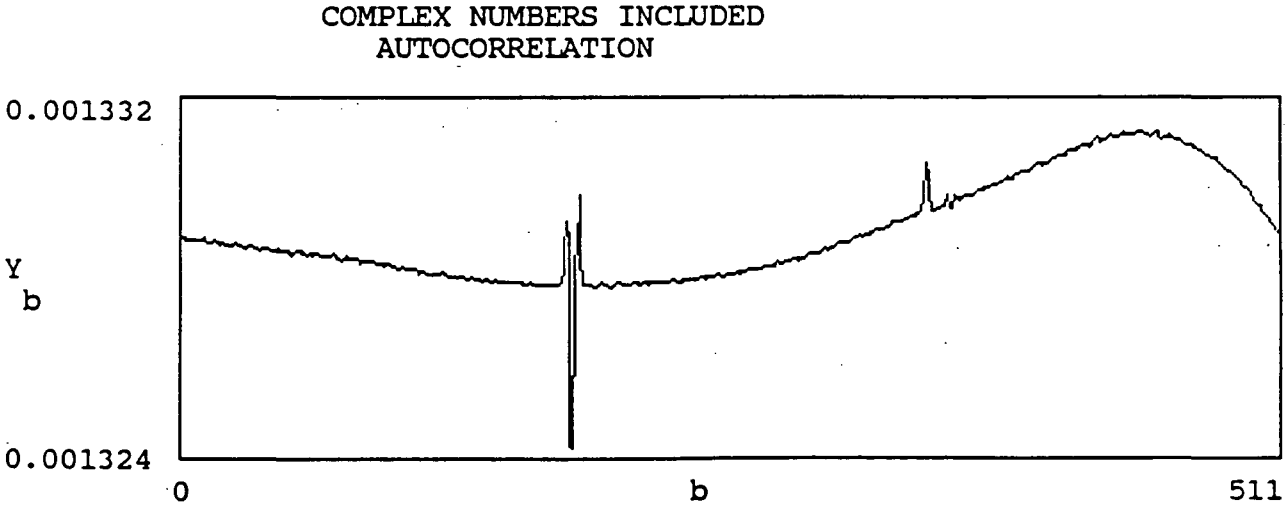
Fig 6e2

$$q_{b+1} := \left[f_{b+1}\right] \cdot \left[f_{b+1}\right]$$

R := ifft(q)



Y := icfft(y)



$m := 10$

$L := 2^m$

$j := 0 \ldots L - 1$

$A := READPRN(M)$

$\sigma_j := A_{j+1} - A_j$

CALL "FILENAME M" FROM COMMAND:

SELECT DRIVE:FILE.PRN

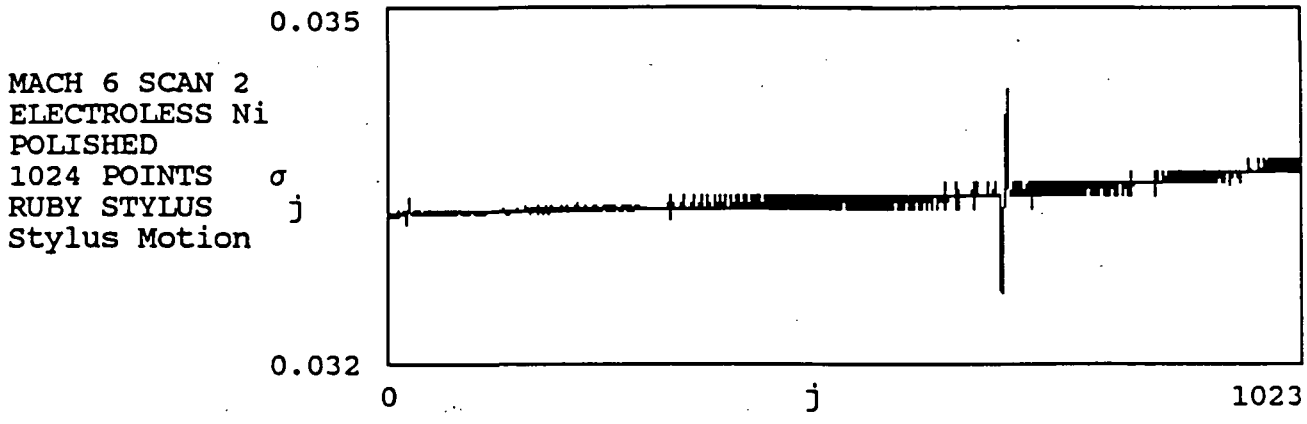
SET UP A VECTOR OF INTERVALS

j MUST = 2^m WITH m A WHOLE NO.

RE-ENTER 'A' AFTER SELECTING FILE

REMOVE TILT BY FORWARD DIFFERENCE

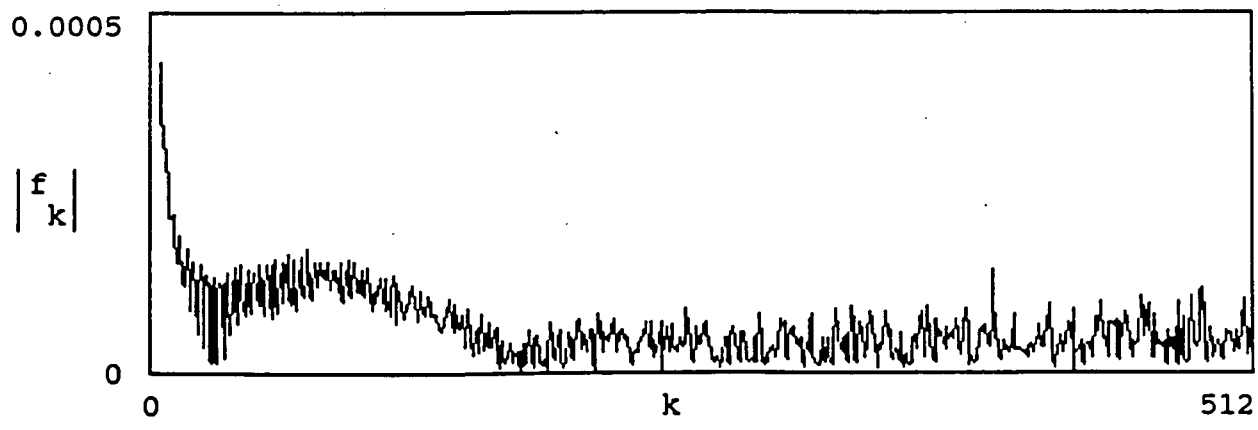
ROUGHNESS DATA



$f := fft(\sigma)$

$k := 0 \ldots 2^{m-1}$

FOURIER TRANSFORM



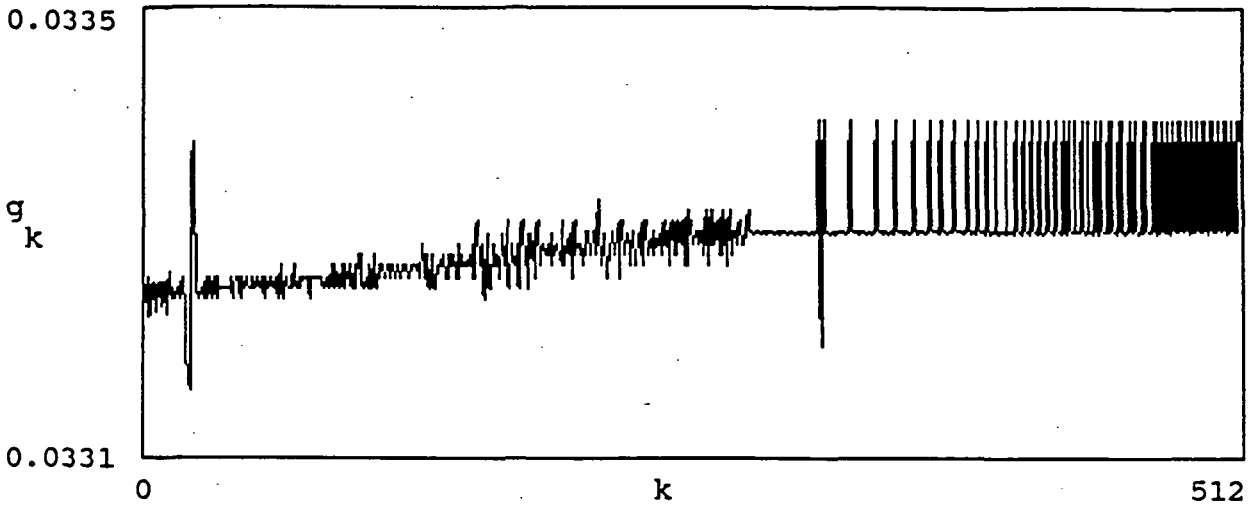
Analysis of Stylus Motion (Second Polish)
Note correlation to
disturbance 6ε1 to 6ε3 (Ruby Stylus)

Fig. 6f1

$g := ifft(f)$

$k := 0 \,..\, 2^{m-1}$

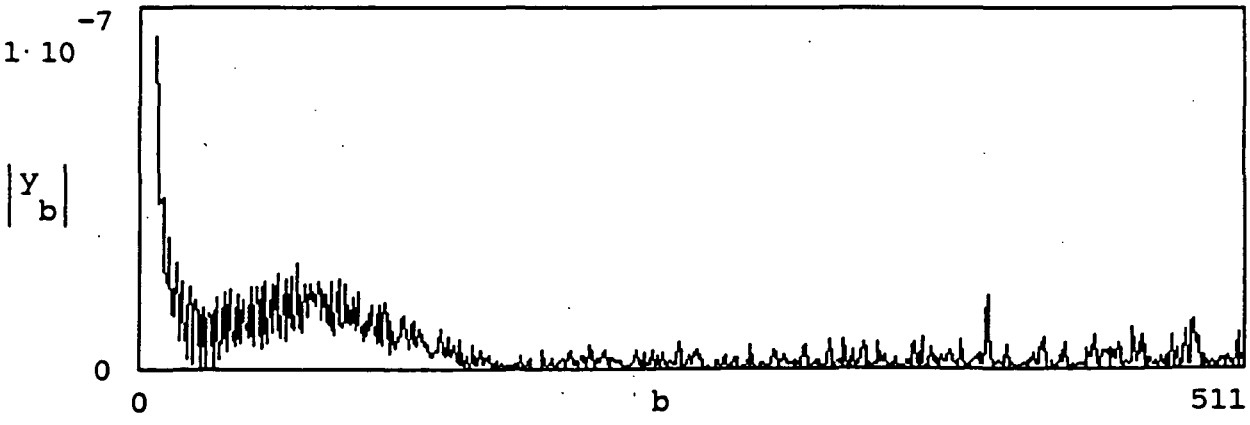
INVERSE TRANSFORM
ORIGINAL SPECTRUM



$b := 0 \,..\, 2^{m-1} - 1$

$y_b := f_b \cdot f_b$

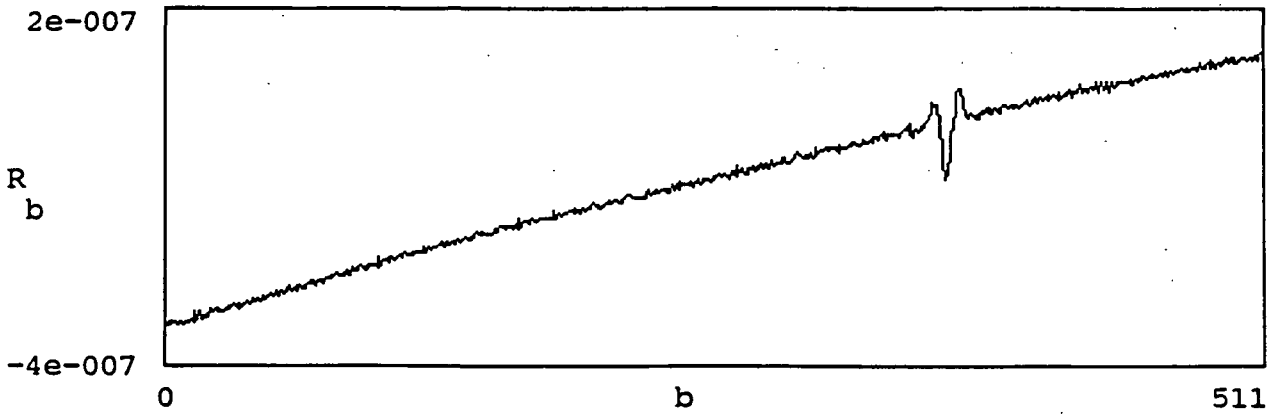
POWER SPECTRUM



$$q_{b+1} := \left[f_{b+1}\right] \cdot \left[f_{b+1}\right]$$

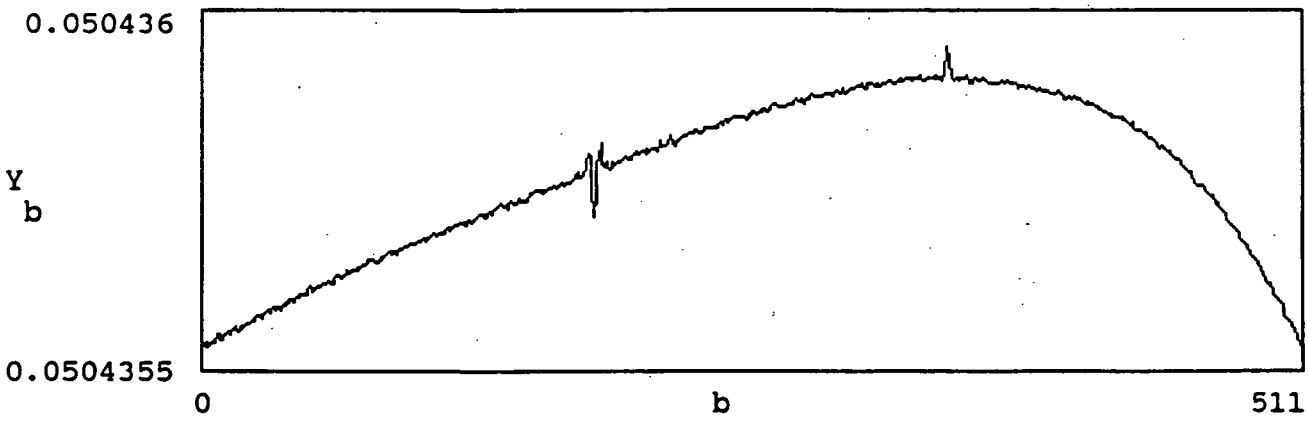
R := ifft(q)

AUTOCORRELATION



Y := icfft(y)

COMPLEX NUMBERS INCLUDED
AUTOCORRELATION



$m := 10$

$L := 2^m$

$j := 0 \ldots L - 1$

$A := READPRN(M)$

$\sigma_j := A_{j+1} - A_j$

CALL "FILENAME M" FROM COMMAND:

SELECT DRIVE:FILE.PRN

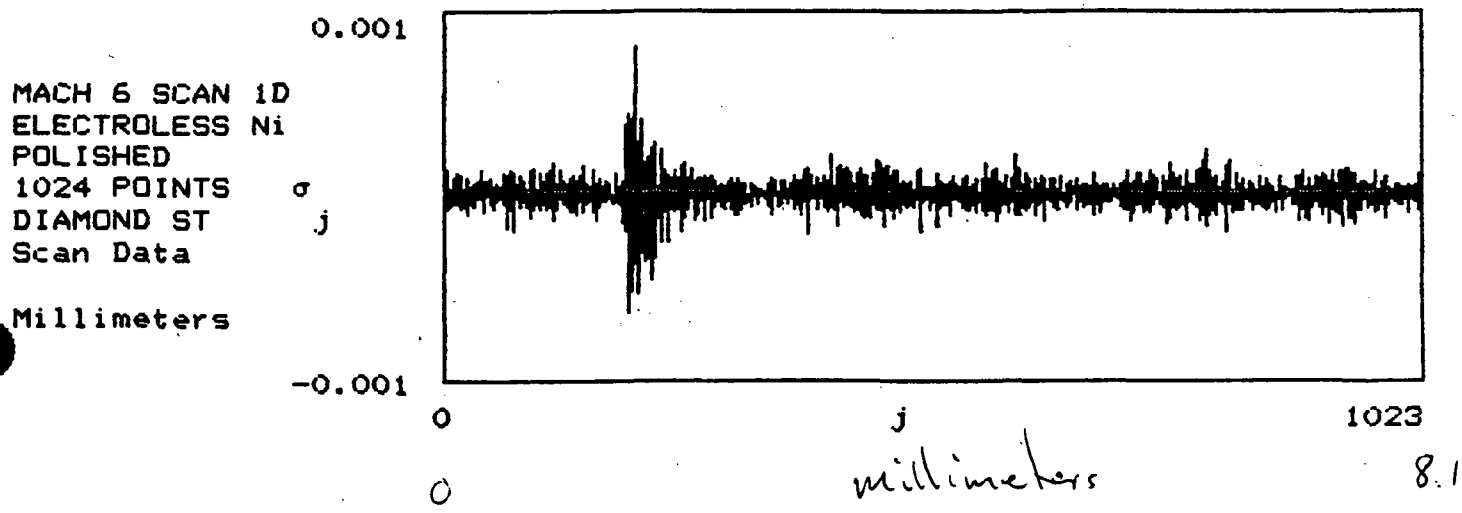
SET UP A VECTOR OF INTERVALS

j MUST = 2^m WITH m A WHOLE NO.

RE-ENTER 'A' AFTER SELECTING FILE

REMOVE TILT BY FORWARD DIFFERENCE

ROUGHNESS DATA



0 millimeters 8.1

$f := fft(\sigma)$

$k := 0 \ldots 2^{m-1}$

FOURIER TRANSFORM

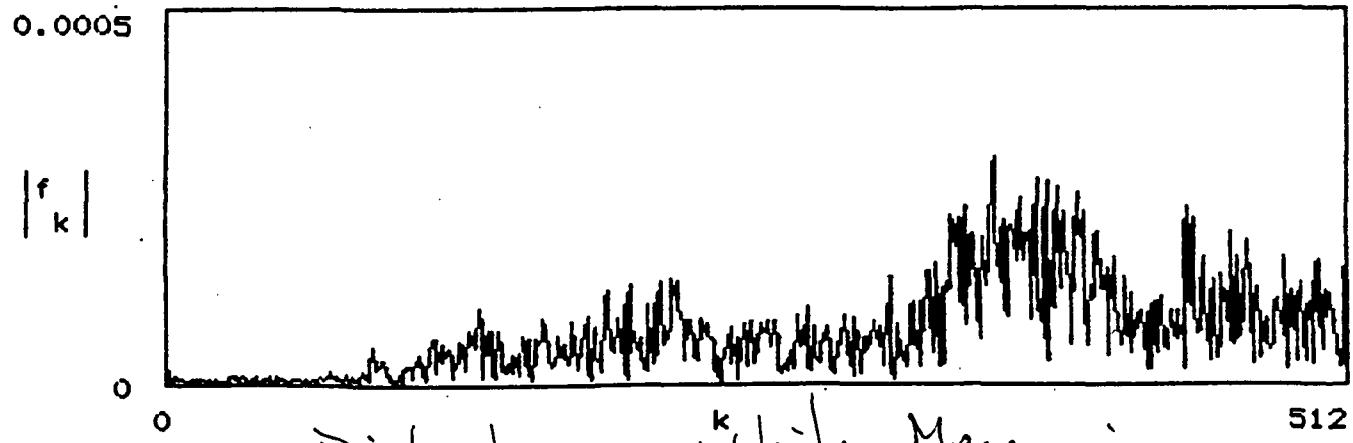
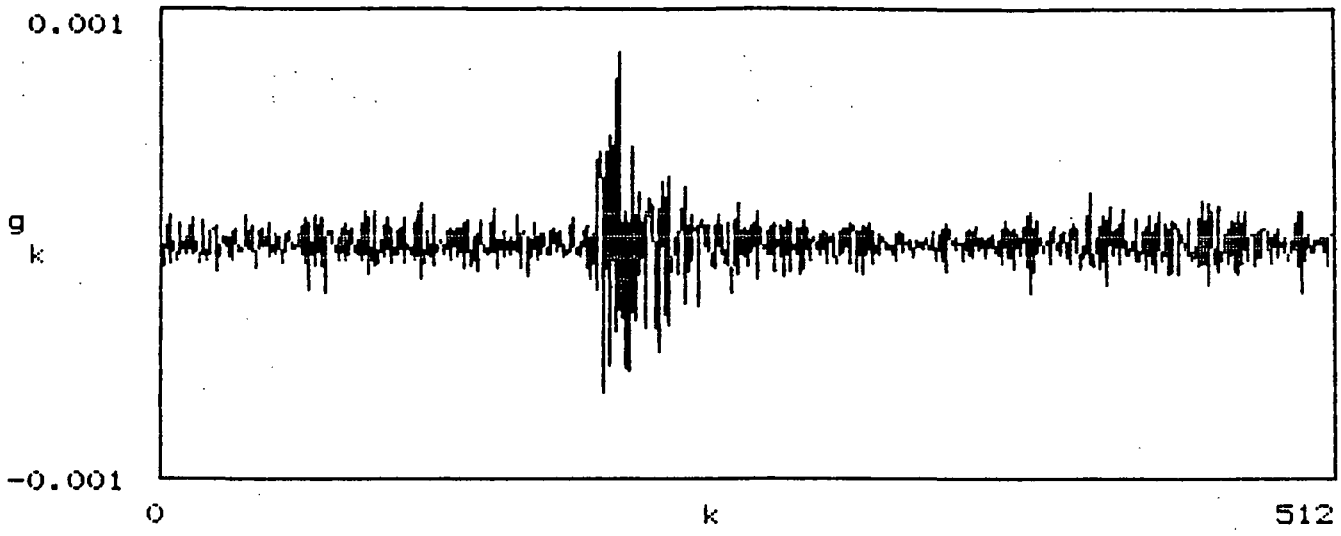


Fig. 6g1 Disturbance while Measuring with Diamond Stylus (Third Polish)

$g := ifft(f)$

$k := 0 \,..\, 2^{m-1}$

INVERSE TRANSFORM
ORIGINAL SPECTRUM



$b := 0 \,..\, 2^{m-1} - 1$

$y_b := f_b \cdot f_b$

POWER SPECTRUM

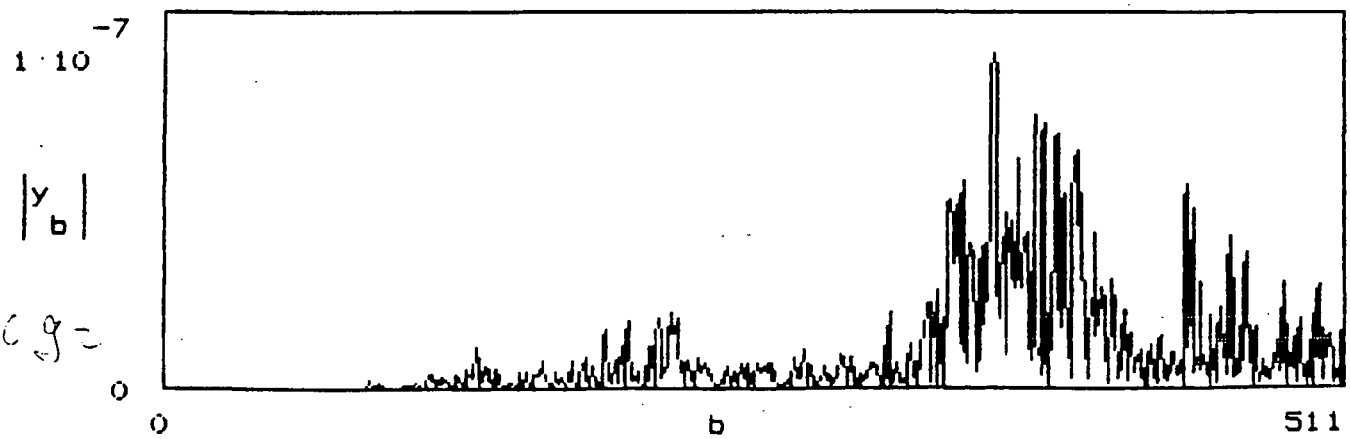
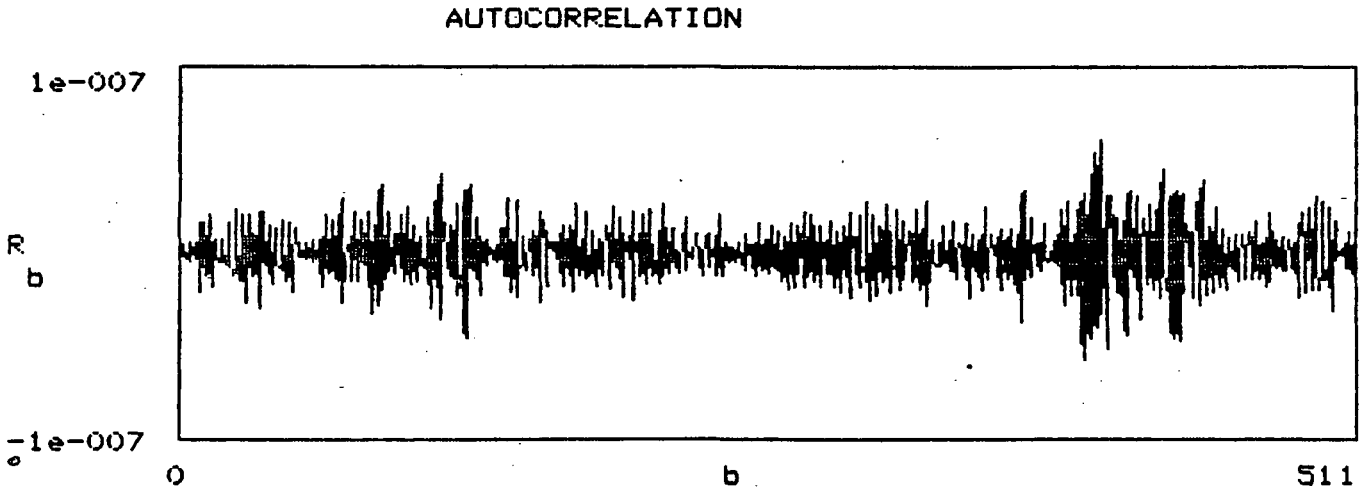


Fig. 6 g=

$$q_{b+1} := \left[f_{b+1}\right] \cdot \left[f_{b+1}\right]$$

R := ifft(q)



Y := icfft(y)

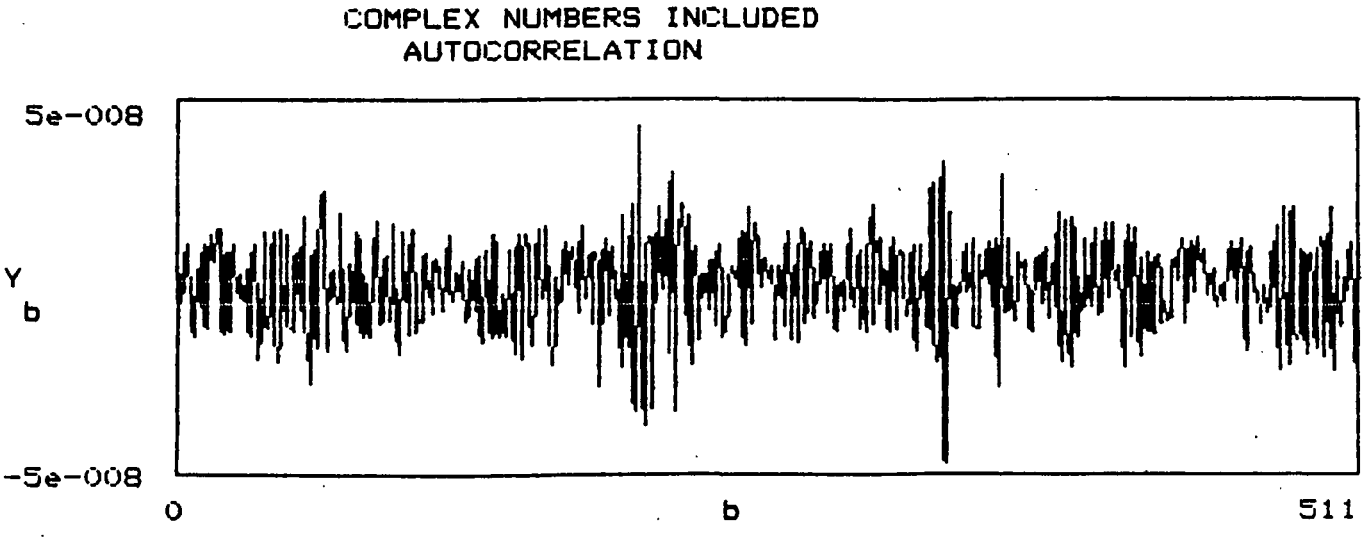


Fig. 693

$m := 9$

CALL "FILENAME M" FROM COMMAND:

$L := 2^m$

SELECT DRIVE:FILE.PRN

$j := 0 \ldots L - 1$

SET UP A VECTOR OF INTERVALS

j MUST = 2^m WITH m A WHOLE NO.

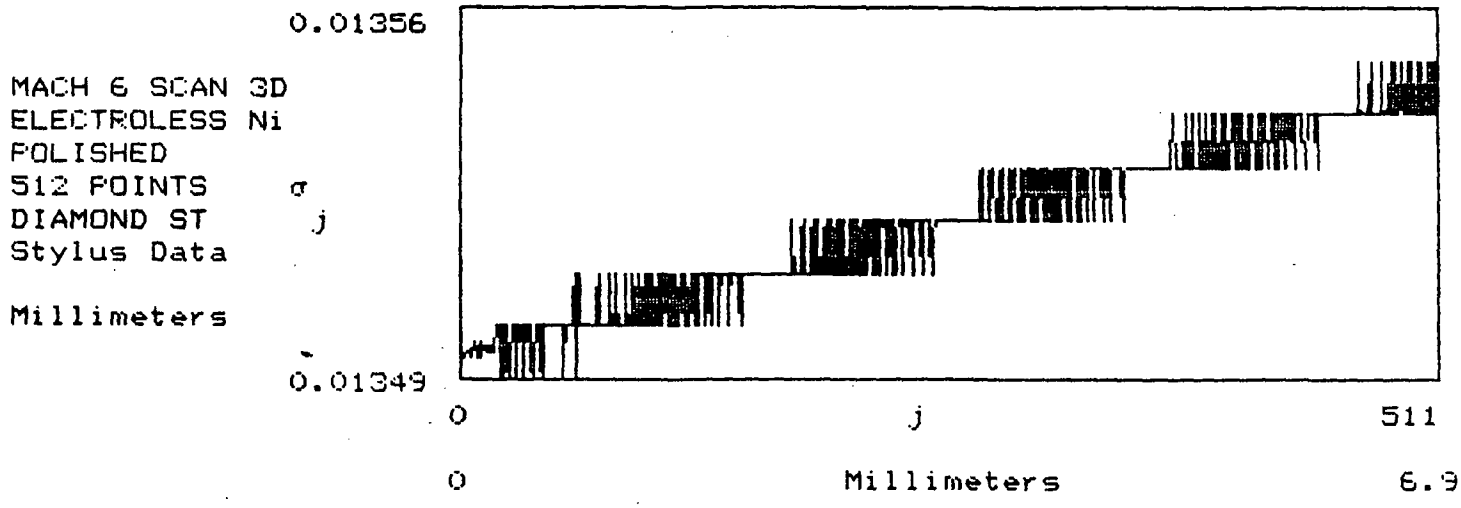
$A := READPRN(M)$

RE-ENTER 'A' AFTER SELECTING FILE

$\sigma_j := A_{j+1} - A_j$

REMOVE TILT BY FORWARD DIFFERENCE

ROUGHNESS DATA



$f := fft(\sigma)$

$k := 0 \ldots 2^{m-1}$

FOURIER TRANSFORM

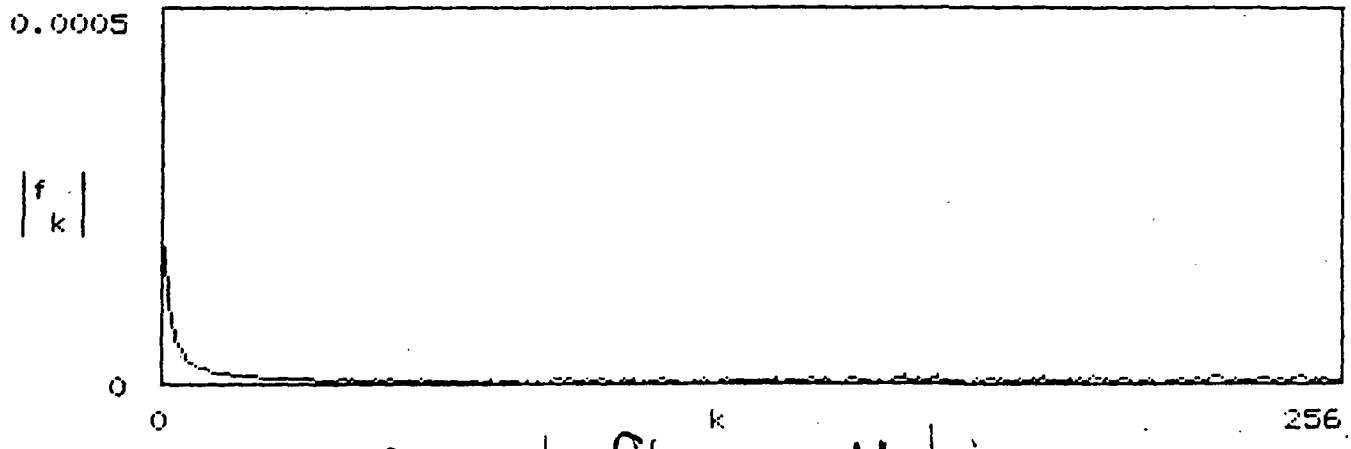
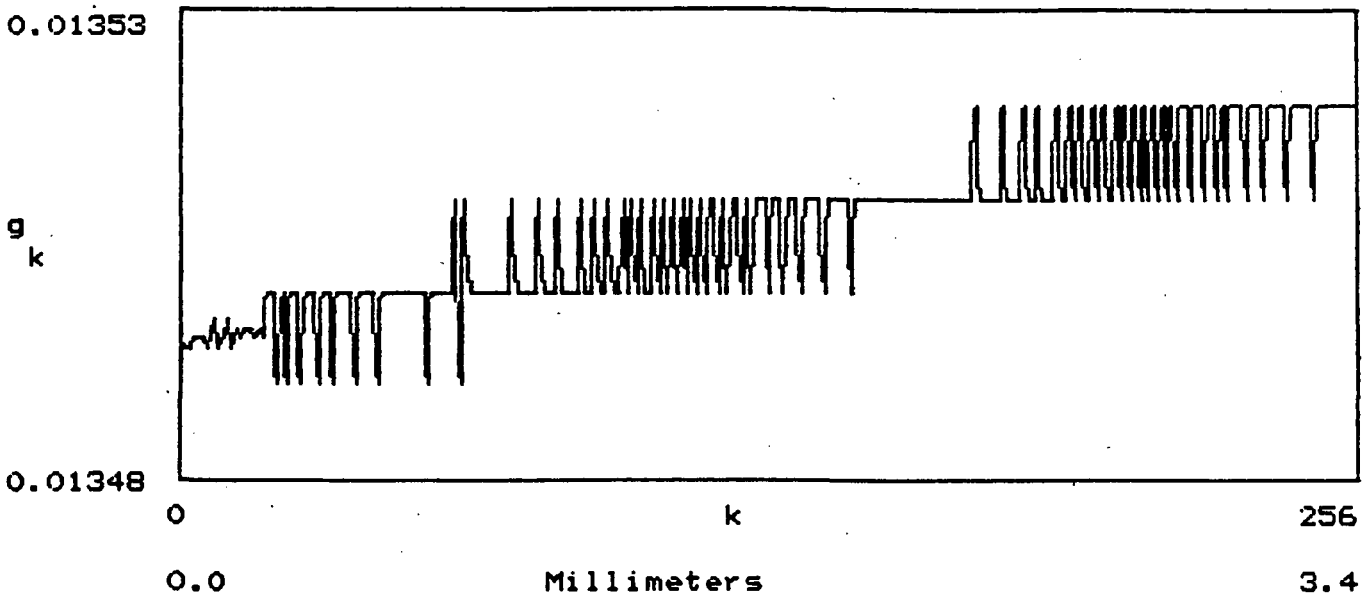


Fig 6 h1 Smooth Stylus Motion

$g := ifft(f)$

$k := 0 \,..\, 2^{m-1}$

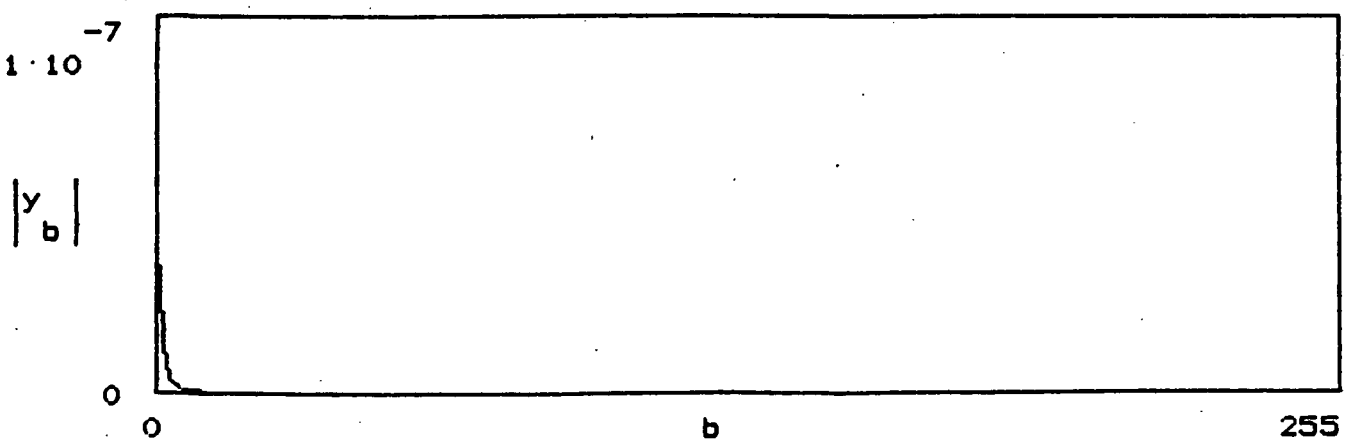
INVERSE TRANSFORM
ORIGINAL SPECTRUM



$b := 0 \,..\, 2^{m-1} - 1$

$y_b := f_b \cdot f_b$

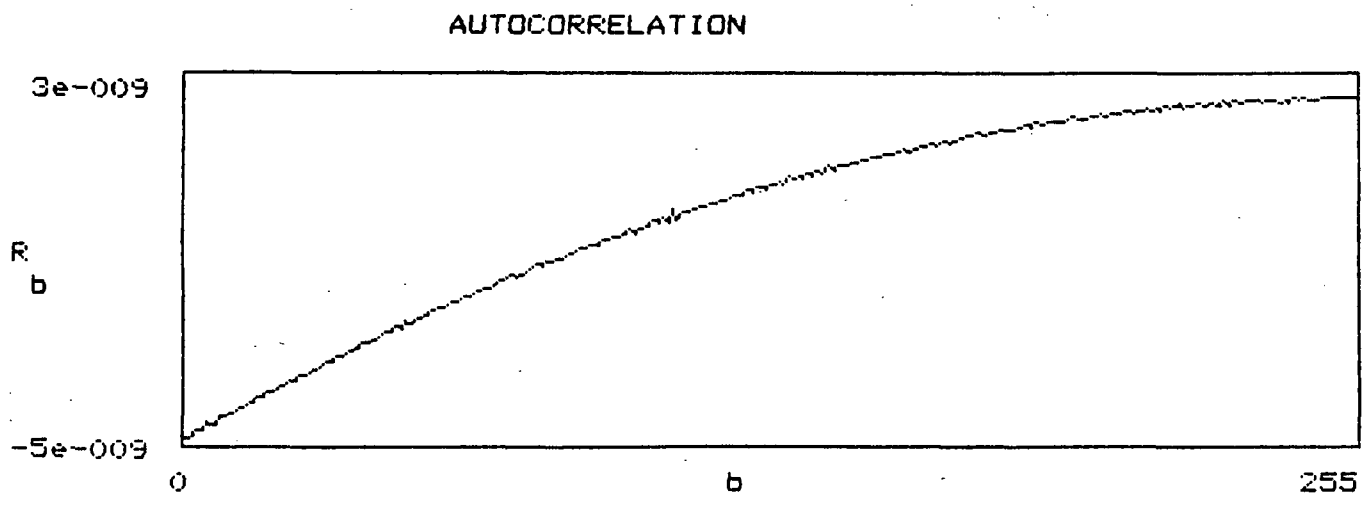
POWER SPECTRUM



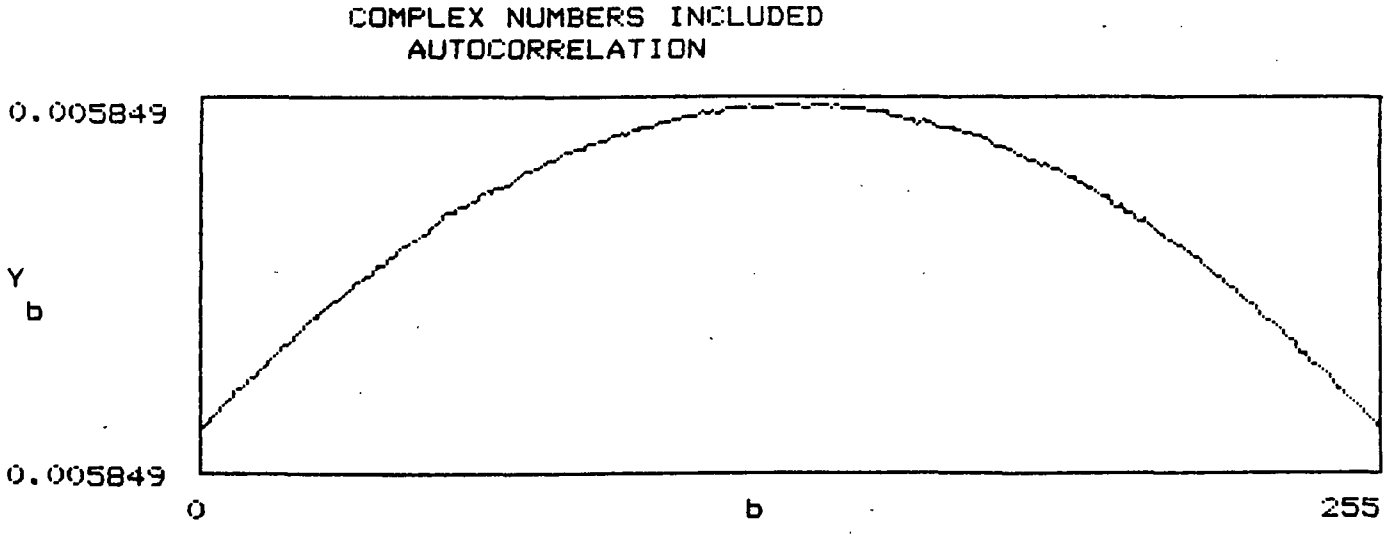
Ghz

$$q_{b+1} := \begin{bmatrix} f \\ b+1 \end{bmatrix} \cdot \begin{bmatrix} f \\ b+1 \end{bmatrix}$$

R := ifft(q)



Y := icfft(y)



6h3

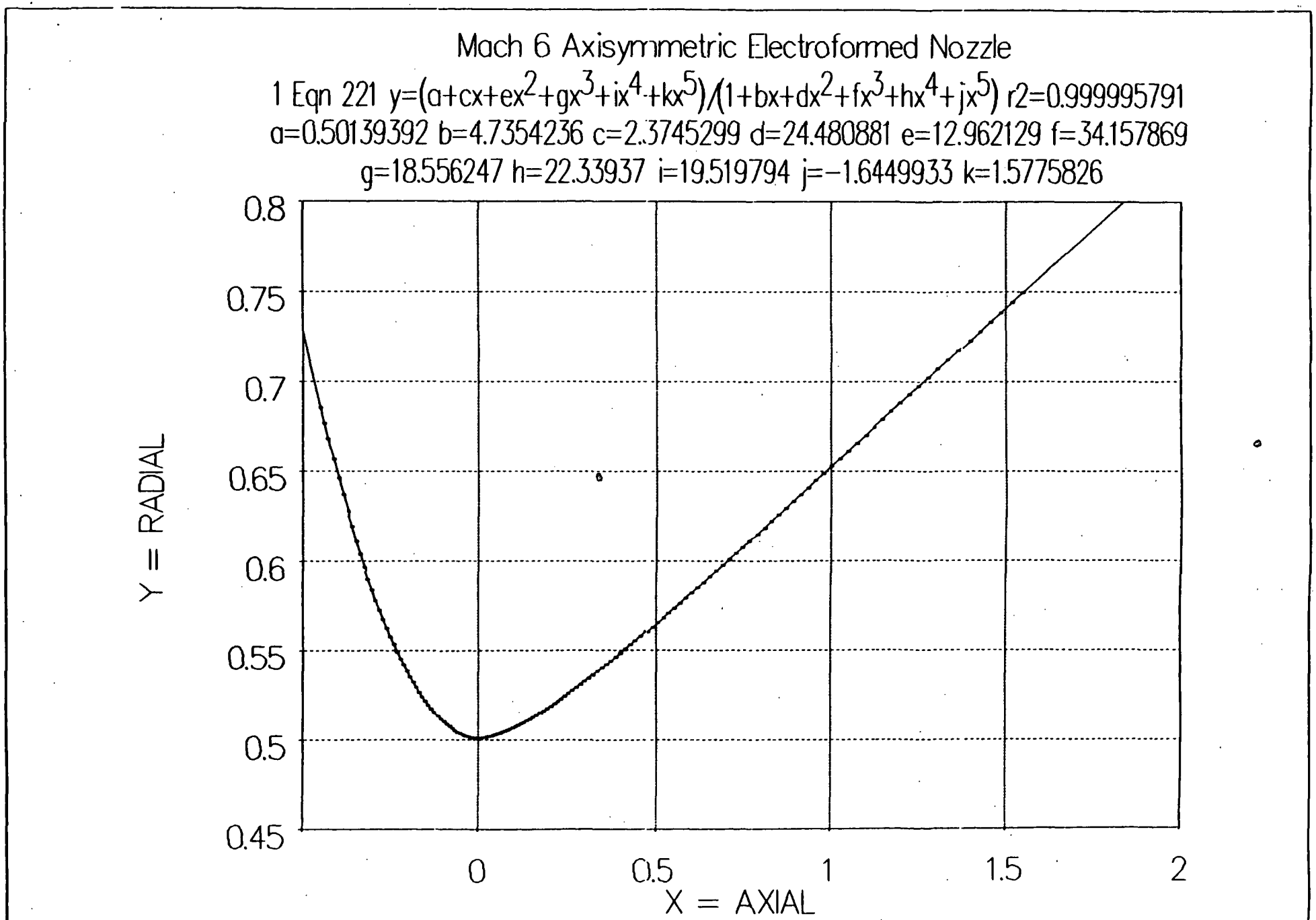


Fig 7a Polynomial Fit (Original Data)

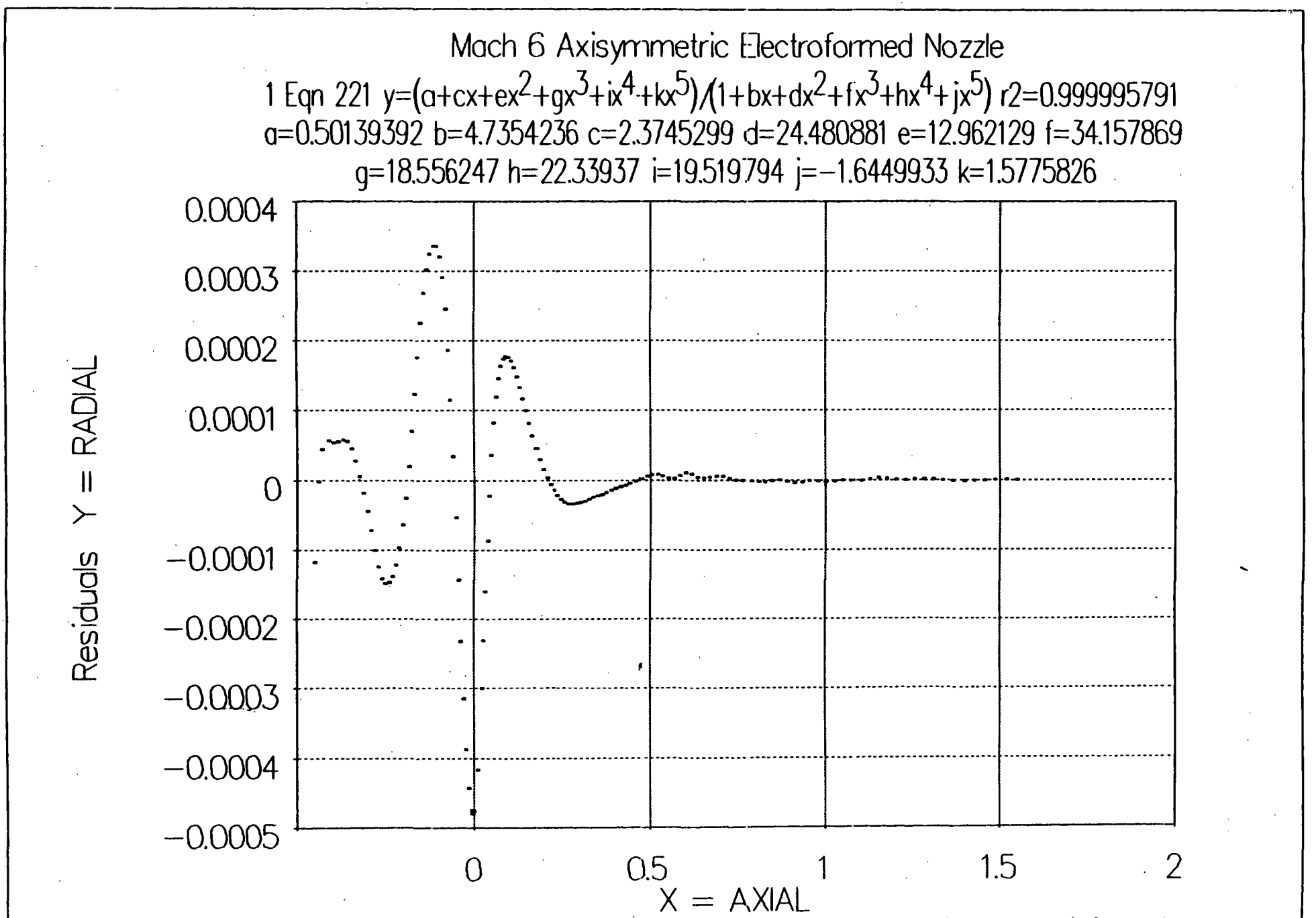


Fig 7b Residual Error at minimum (Original Data)

Aug 24,1991 9:09 AM

Description: Mach 6 Axisymmetric Electroformed Nozzle
X-Y Table Size: 145 Active Points: 145

X Variable: X = AXIAL

Xmin:	-0.45	Xmax:	1.550052	Xrange:	2.000052
Xmean:	0.319499182	Xstd:	0.524151831	Xmedian:	0.1855092
X@Ymin:	-0	X@Ymax:	1.550052	X@Yrange:	1.550052
Xav@Ymax:	1.518546	X@50Y:	0.909221781	Xlt@50Y:	0
Xrt@50Y:	0	X@25Y:	0.79987469	X@75Y:	0.554691769
Xwavemin:	0.041181181	Xwavemax:	1.4876376	Xwaverng:	2.892912838

Y Variable: Y = RADIAL

Ymin:	0.50091795	Ymax:	0.74926858	Yrange:	0.24835063
Ymean:	0.572669332	Ystd:	0.069513562	Ymedian:	0.54907469
Y@Xmin:	0.68538	Y@Xmax:	0.74926858	Y@Xrange:	0.06388858

1 Eqn 221 y=(a+cx+ex2+gx3+ix4+kx5)/(1+bx+dx2+fx3+hx4+jx5) r2=0.999995791

	Coefficient	Std Error	T(Coef/Err)	95% Confidence Limits	
a	0.501393923	3.1263e-05	16037.86742	0.501332087	0.50145576
b	4.735423572	0.103477031	45.76304054	4.530753048	4.940094097
c	2.3745299	0.052239013	45.45510617	2.271204687	2.477855113
d	24.48088073	0.576991113	42.42852305	23.33963159	25.62212988
e	12.96212871	0.292064467	44.38105344	12.38444507	13.53981234
f	34.15786936	1.117449906	30.56769631	31.94762951	36.36810921
g	18.55624747	0.575846915	32.22427176	17.41726147	19.69523347
h	22.33936968	0.98445393	22.69214333	20.39218682	24.28655255
i	19.51979428	0.742084312	26.30401151	18.05200202	20.98758654
j	-1.64499332	0.040482809	-40.6343665	-1.72506556	-1.56492108
k	1.577582582	0.118474251	13.31582665	1.343248579	1.811916586

Curve-Fit Std Error: 0.000147838953917

Source	Sum of Squares	DF	Mean Square	F
Regr	0.69582455	10	0.069582455	3.18363e+06
Error	2.9287517e-06	134	2.1856356e-08	
Total	0.69582748	144		

Fig 7c Polynomial Data & Coefficients

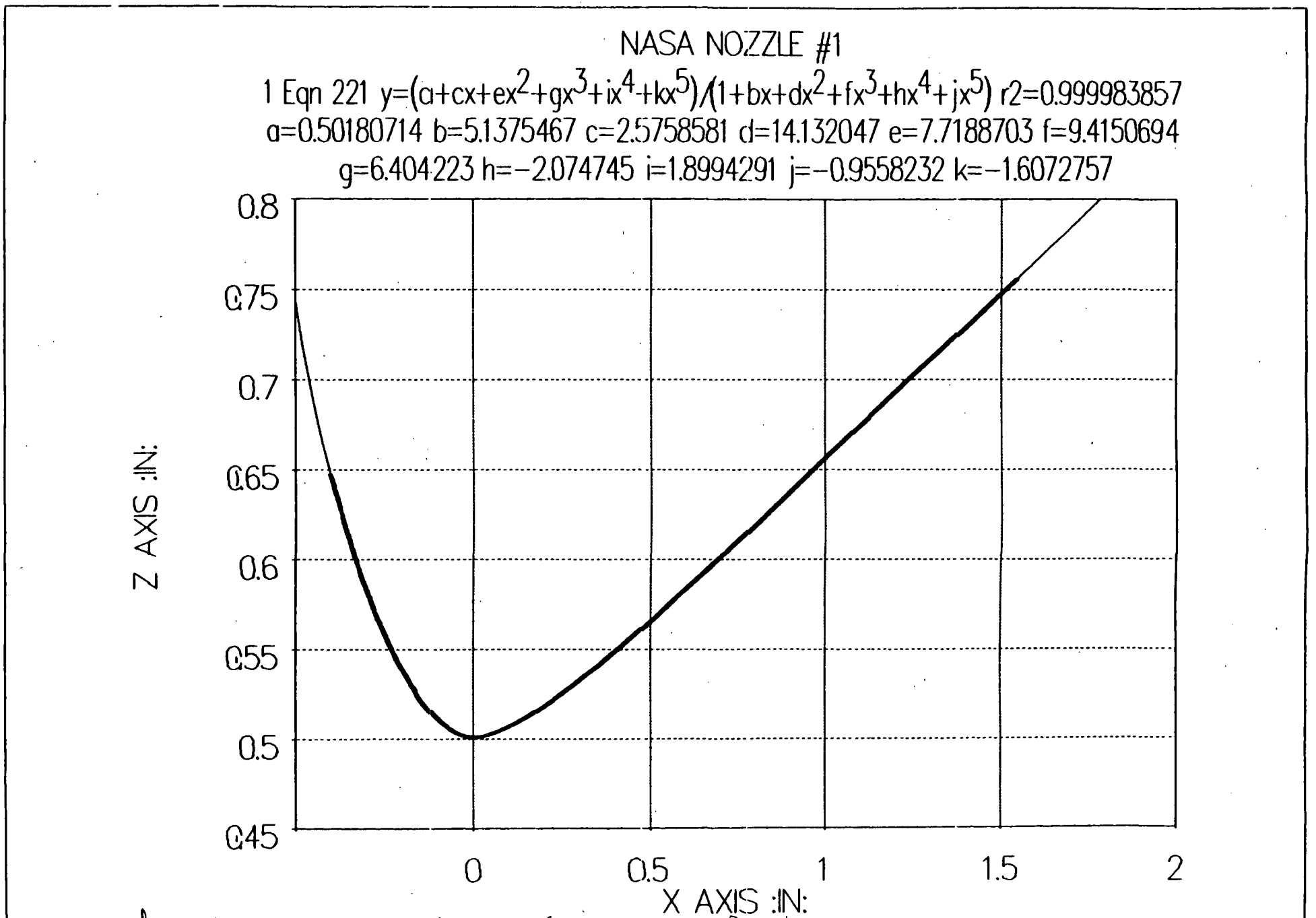


Fig 7d Polynomial Fit (Measured Data)

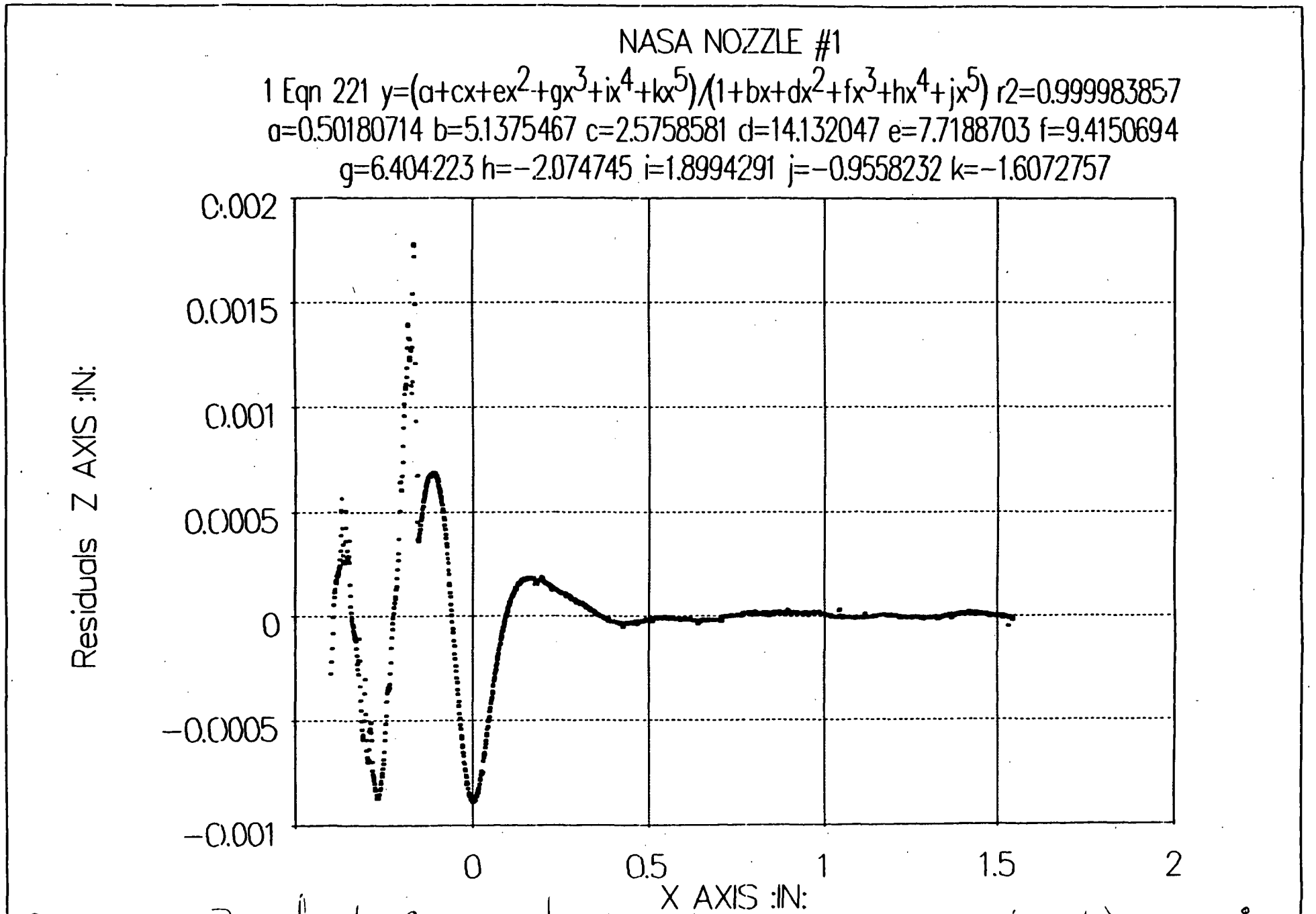


Fig. 7e Residual Error at Minimum (Measured Data)

ug 24,1991 10:24 AM

Description: NASA NOZZLE #1
X-Y Table Size: 1458 Active Points: 1458

X Variable: X AXIS :IN:

Xmin:	-0.40236614	Xmax:	1.544735709	Xrange:	1.94710185
Xmean:	0.581011493	Xstd:	0.559774472	Xmedian:	0.583165354
X@Ymin:	0	X@Ymax:	1.544735709	X@Yrange:	1.544735709
Xav@Ymax:	1.50991136	X@50Y:	0.34958759	Xlt@50Y:	0
Xrt@50Y:	0	X@25Y:	0.996751199	X@75Y:	1.194492873
Xwavemin:	0.052184974	Xwavemax:	1.475074623	Xwaverng:	2.845779298

Y Variable: Z AXIS :IN:

Ymin:	0.50091795	Ymax:	0.755710863	Yrange:	0.254792913
Ymean:	0.604218023	Ystd:	0.077285612	Ymedian:	0.593951198
Y@Xmin:	0.647127399	Y@Xmax:	0.755710863	Y@Xrange:	0.108583465

1 Eqn 221 y=(a+cx+ex2+gx3+ix4+kx5)/(1+bx+dx2+fx3+hx4+jx5) r2=0.999983857

	Coefficient	Std Error	T(Coef/Err)	95% Confidence Limits	
	0.501807141	2.5027e-05	20050.97159	0.501758149	0.501856133
	5.137546651	0.087525373	58.69779765	4.966206948	5.308886354
c	2.575858111	0.044190494	58.28986847	2.489350783	2.662365439
d	14.13204683	0.247638195	57.06731473	13.64727021	14.61682345
e	7.718870333	0.125001151	61.75039404	7.474168033	7.963572632
f	9.415069363	0.344204408	27.35313423	8.741254688	10.08888404
g	6.404223003	0.187269877	34.19782786	6.037623424	6.770822582
h	-2.07474503	0.370435859	-5.60082126	-2.79991041	-1.34957966
i	1.899429085	0.253783683	7.48444132	1.402622053	2.396236117
j	-0.9558232	0.019200372	-49.7814935	-0.99340986	-0.91823655
k	-1.60727569	0.053671304	-29.9466489	-1.71234266	-1.50220873

Curve-Fit Std Error: 0.000311595279987

Source	Sum of Squares	DF	Mean Square	F
Regr	8.7026165	10	0.87026165	8.9633e+06
Error	0.00014049157	1447	9.7091619e-08	
Total	8.702757	1457		

7f Polynomial Data & Coefficients

WIND TUNNEL DATA
MACH 6 ELECTROFORMED

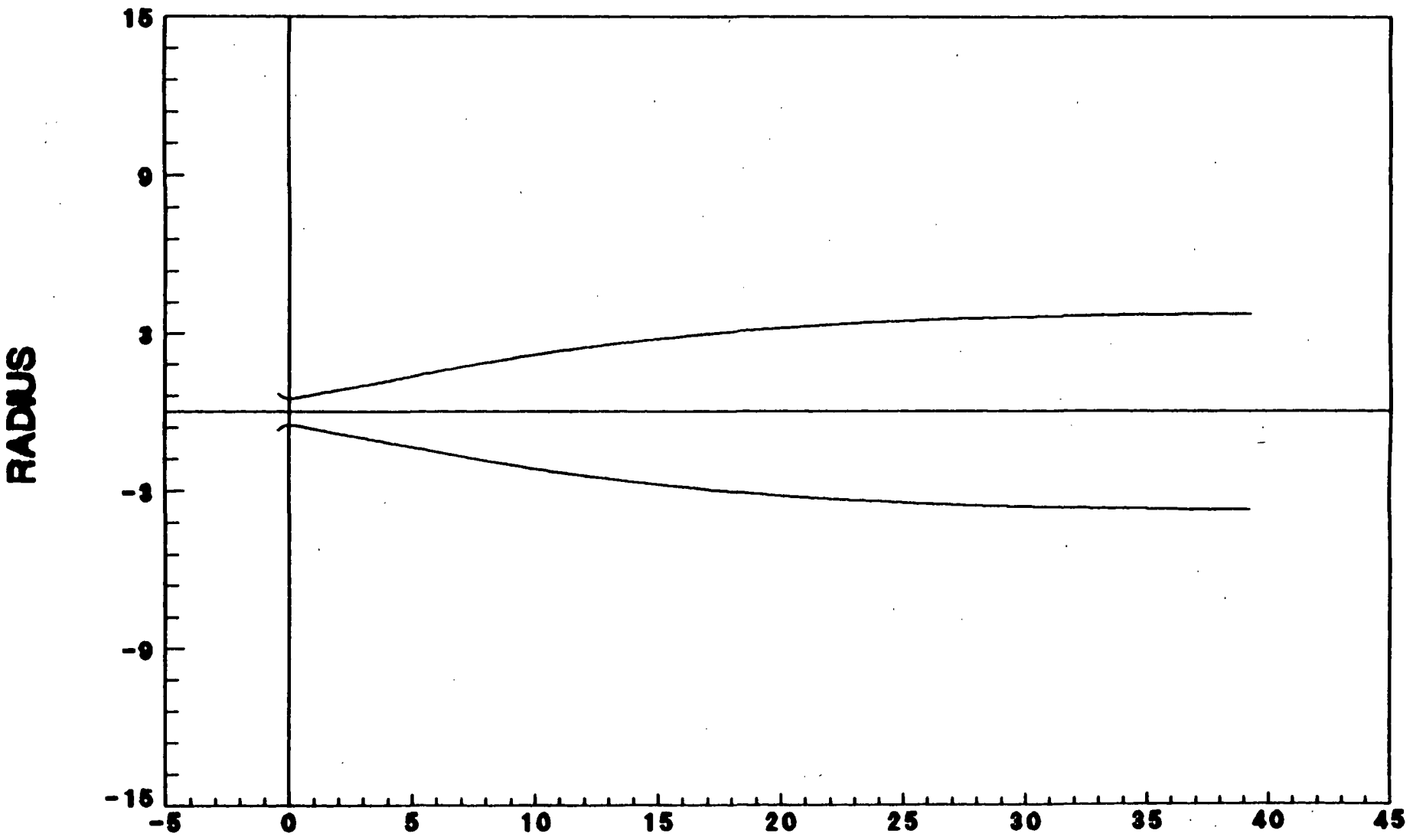


Fig 79 Original Data

WIND TUNNEL DATA
MACH 6 ELECTROFORMED

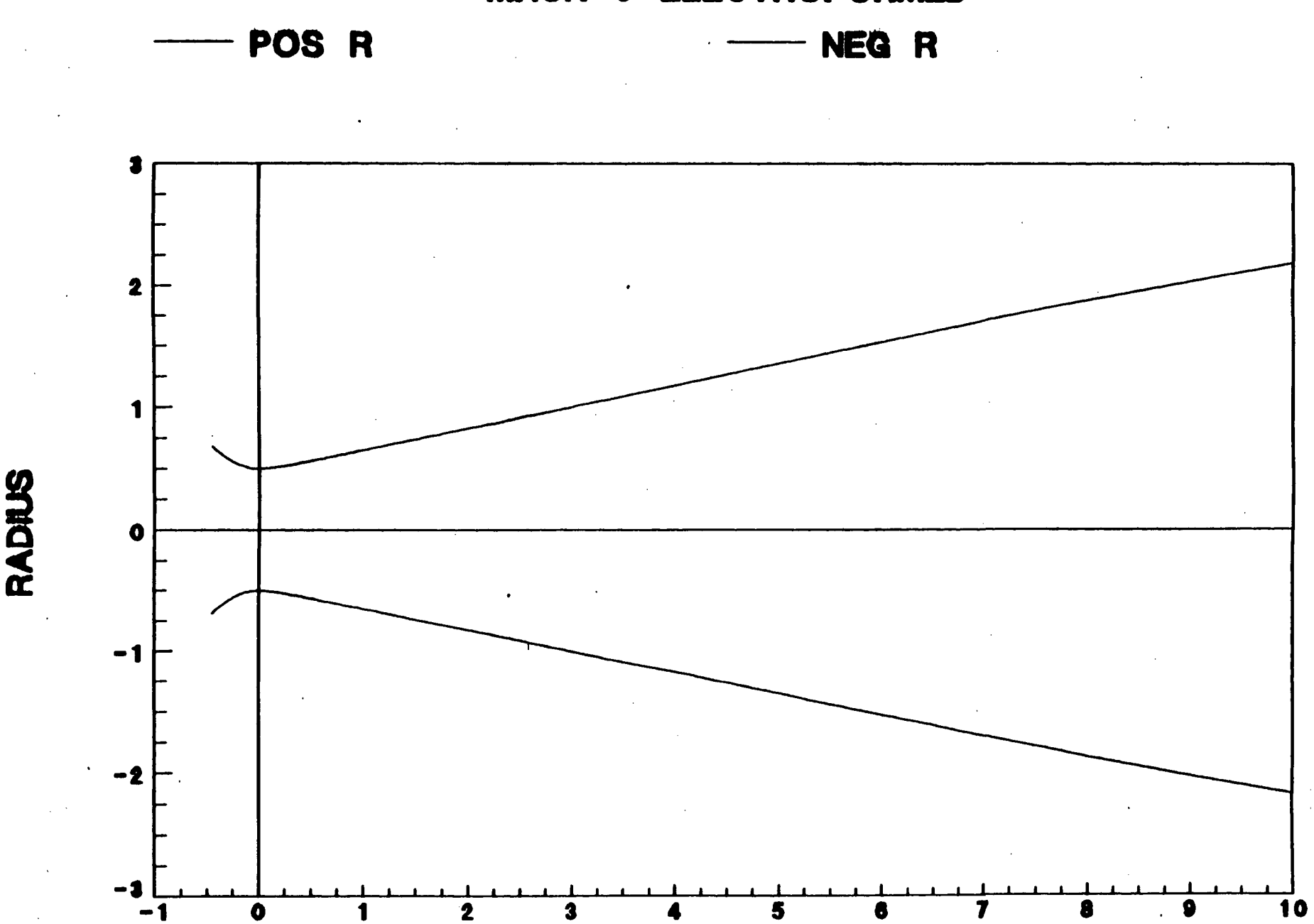


Fig 7h Original Data

APPENDIX II. Additional Photos by MSFC

APPENDIX III

Suggested Plating Process

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

JUNE 1991

CONTRACT TITLE: WIND TUNNEL REFURBISHMENT

AGENCY: NASA MARSHALL SPACE FLIGHT CENTER

DESCRIPTION: ELECTROLESS NICKEL PLATING ON ELECTROFORMED NICKEL

Two electroformed nickel components will be coated with 0.0015 inches of nickel-phosphorous alloy. The deposit quality must support subsequent polishing to near optical quality mirror surfaces. The nickel alloy deposit will be reduced by about 0.00025 -0.0005 inches thickness when polished to achieve the optical surface required. It is therefor imperative that the nickel deposit be of very high quality to avoid pitting or poor adhesion. The nickel alloy must be at least 10 weight percent phosphorous and may contain up to 2 additional weight percent copper. Chemical etching to improve adhesion is acceptable. No more than 0.0005 inches of the original electroformed nickel surface shall be removed by any etching process. The entire outer structure is 304 stainless steel and should not be plated unless absolutely necessary. Contact NASA for approval if required.

Processes known to produce suitable deposits when properly operated include but are not limited to the following:

Shipley NICULLOY - 22

Shipley DURAPOSIT - 90

Shipley NIPOSIT - 468

Enthone ENPLATE NI - 425

Enthone ENPLATE NI - 418

McGean ROHCO

M&T Chemicals INC.

The plating is specified to MIL-C-26074D (Feb. 1989). Drawing notes have precedence over the MIL Standard.

The heat treatment is to be 320 $\pm$ 10 Deg. F.

The thickness requirement is 0.0015 - .002 inches.

A reference sample will be plated for alloy check and pitting. This alloy sample will be submitted to NASA prior to plating approval for the parts. A bend sample strip per the MIL-C-26074D will be plated and adhesion tested by the supplier.

Vendors must state if they have successful experiences with electroless nickel plating for the purpose of producing polished optical quality surfaces.

Pitting of the electroless nickel deposits may be related to both the process quality and the plating process control. The acceptable plating process will address both by comprising appropriate cleaning and activation steps. One such step is to use a solution of reducing acids for removing trace impurities prior to plating. The original electroformed nickel surface will contain nickel oxide as well as trace impurities. A common solution for the removal of impurities from the surface of electroformed nickel consists of a mixture of hydrochloric and sulfuric acids which require caution for acceptable safety. About 25 Volume percent of each acid (at the standard concentrated value) is required mixed with 50% de-ionized water. The standard concentrated value is 98% for sulfuric acid and about 33% for hydrochloric acid. This solution is used at 120 Degrees F. An alternate process is to use dilute nitric acid (5% by volume of the 67% concentrated acid) at 120 Degrees F.

An adhesion test must be performed by plating a sample of electrodeposited nickel with the electroless process and performing a bend test to determine that no flaking or peeling due to poor adhesion occurs. The sample must be bent 180 degrees over a cylindrical mandrel with a diameter which is 4 times the combined thickness of the substrate and the deposit. A substrate no more than 0.040 inches and no less than 4 times the deposit thickness shall be used. For this task a substrate 0.006 to 0.008 inches thick, plated to 0.0015 - 0.002 inches with the electroless nickel and bent over a mandrel 0.030 - 0.040 inches in diameter would be ideal.

Additional precautions include vendor process control of filtration, agitation and heating as well as chemical analysis and control. The deposition of .0015 - 0.002 inches of electroless nickel-phosphorous represents about 4 hours of plating during which additions will be required to the solution. Automatic controllers are available and assist in the control but are not mandantory.

Parts of high value are typically monitored continuously by the plating personnel. The deposition can be stopped and restarted if trouble occurs for some operations but may leave a striation in the deposit which would manifest as defective lapping later. Therefor the requirements must include <u>uninterrupted plating</u>.

Alloy control is typically specified and may vary within the part. The specification of +/- 1% is acceptable. An alloy average check by chemical analysis of a coupon sample is appropriate and if the overall average is good then the opportunity for the component to be out of specification is low.

Many parts can be stripped and replated if needed and will not be damaged if stripping is not repeated many times. However stripping of electroless nickel-phophorous from pure nickel will damage the nickel surface. Therefor the parts are not to be stripped and replated unless expressed permission is given by NASA.

Any vendor considered should demonstrate a thorough knowledge of the analytical requirements for his plating process and precision requirements of the final components.

An agreement that visible pitting is unacceptable should be obtained prior to contracting for this work. A thorough knowledge of precision masking and plating is required.

Suggested vendors include:

ACTERON CORPORATION
851 SHASTA STREET
REDWOOD, CA 94063
415/369-5217 415/364-9748 FAX
ATT. HANS SELLGE

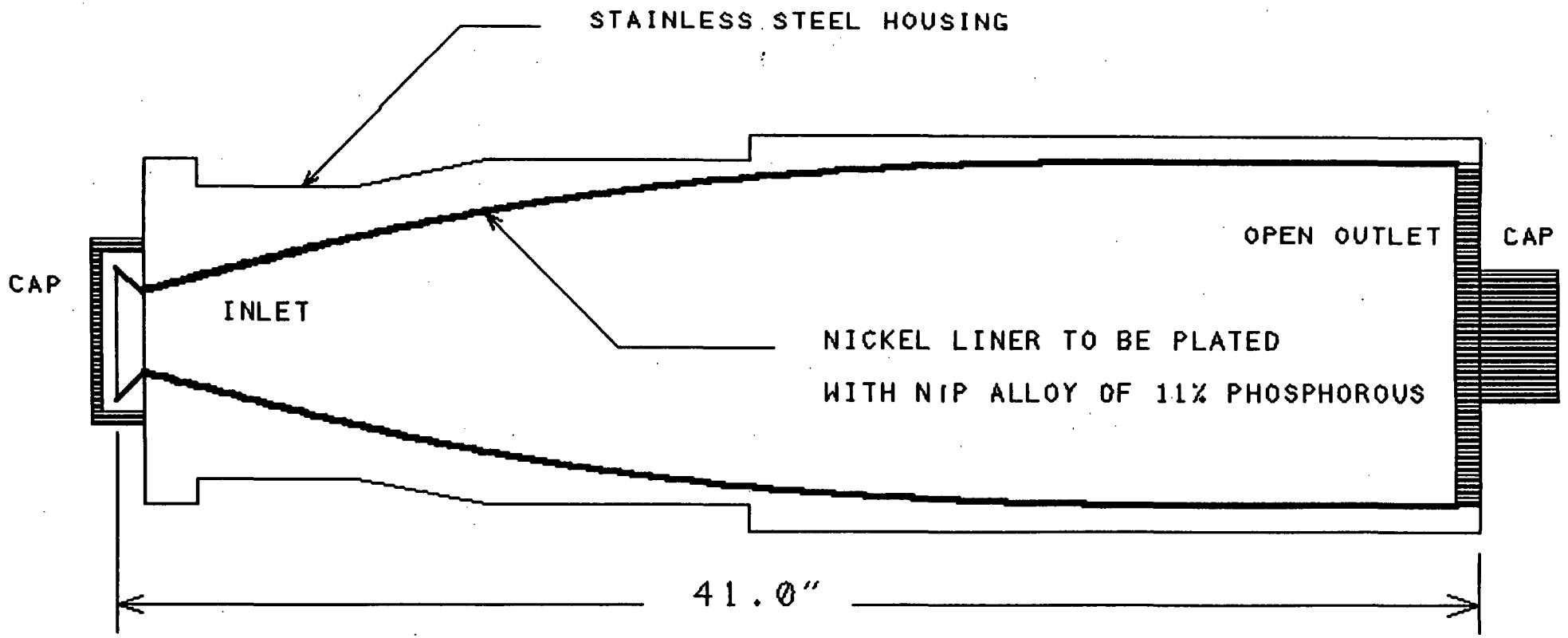
SPEEDRING COMPANY
PO BOX 5393
HUNTSVILLE, AL 35814
205/837-3606 HUNTSVILLE, AL
205/739-1710 CULLMAN, AL (FAX)
ATT. JACK McCLANAHAN

MRC INC.
6455 PARKLAND DRIVE
SARASOTA, FL 34243
813/753-8707
ATT. DAVID HOUSE

METAL SURFACES INC.
6060 SHULL STREET
BELL GARDENS, CA 90201-0521
714/521-4112
ATT. RICK SCHNECK

D. Engelhaupt

NASA / UNIVERSITY OF ALABAMA IN HUNTSVILLE



NASA-MSFC-C

INLET HAS FRAGILE ROLLED LIP
WHICH MUST BE PRESERVED.
UNIT IS AXISYMMETRIC.
PLATING TO BE 0.0015 THICKNESS.

MACH 6 ELECTROFORMED NICKEL NOZZEL
APPROXIMATE WEIGHT 320 LBS.
PLATE WITH ELECTROLESS NICKEL-PHOSPHOROUS
INSIDE ONLY - MASK ALL OTHER SURFACES.