THE DESIGN OF AN ULTRA-PRECISION CNC MEASURING MACHINE

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The Design Phase for an Ultra-Precision CNC Measuring Machine is Complete

DESIGN OBJECTIVES INCLUDED:

- **Inspection of inner and outer surfaces of hemispherical shells and other axisymmetric parts.**
- **Vertical part orientation**
- **400 mm maximum part diameter**
- **250 mm maximum part height**
- **625 mm/min contouring velocity**
- **0.35 mm data point spacing**
- **80 Hz first structural mode**
- **Overall accuracy of 0.75 μm per surface in contouring mode**

THE INSTRUMENT IS KNOWN AS THE CERTIFICATION OF PROCESS (COP) GAUGE

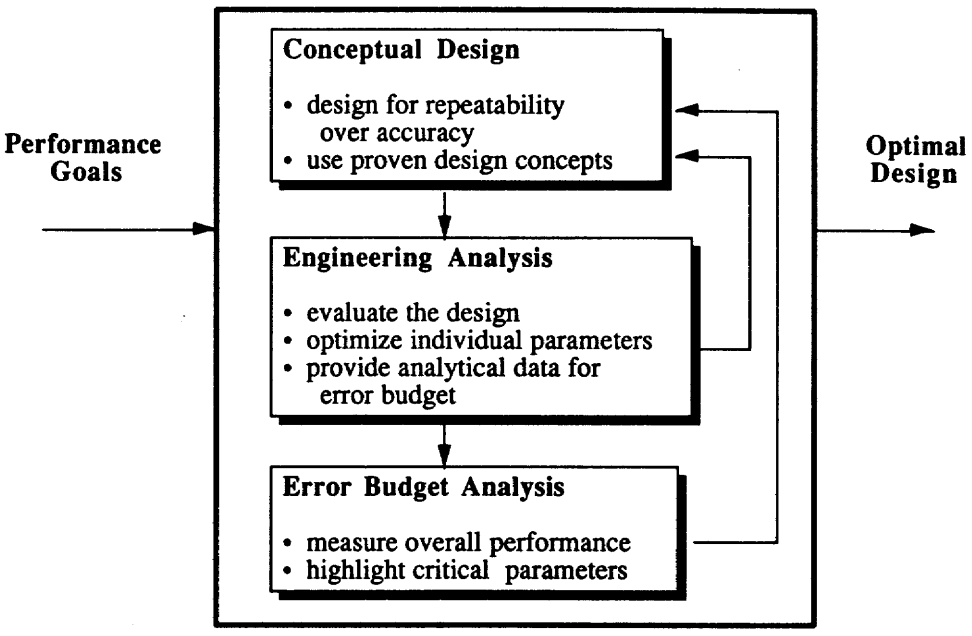
To Balance Performance, Risk and Cost Objectives, The Design Methodology Included

- **Design for repeatability over absolute geometrical accuracy**
  - Error characteristics compatible with error compensation system
- **Use of proven design concepts**
  - Minimum risk, known performance
- **Engineering analysis**
  - Finite element analysis
  - Error budgeting

These elements are iterated to ensure that cost and performance objectives are optimized

Features of the COP Gage Design Include

- **Granite base**
- **3 Linear axes, 1 rotary axis**
- **Air bearings for all axes**
- **Evacuated laser interferometer beam paths**
- **Capstan drives**
- **Super Invar or Zerodur for thermally sensitive components**
- **Air bearing LVDT probes**
- **Air bearing counterpoise cylinders**
  - Pressure servoed to slide drive motor current
- **LLNL-developed CNC and data acquisition system**



The Formulation of the Error Budget Included

- Machine, probe and process errors
- 400 mm diameter stable hemispherical shell
- 360 continuous path polar sweeps per surface
- 1° x 1° data spacing
- Seperate budgets for inner and outer surface measurements
- Peak-to-valley magnitudes of parametric error sources tabulated according to direction

The Selection of an Appropriate Combinatorial Rule Was Not Obvious

- Arithmetic sums of directional (Y-Z) errors yield a conservative upper bound
- RMS sums of directional errors yield an optimistic lower bound (assumes random errors)
- Hocken suggests using the means of the upper (arithmetic) and lower (RMS) limits
- Maximum surface-normal error calculated as the vector sum of the Y and Z errors

Validity of the Combinatorial Rule was Tested by Evaluating an Existing Machine

- 2-Axis precision CNC lathe
- Parametric accuracy testing of individual error sources
- Disc check for evaluation of overall contouring accuracy

ORIGINAL COP GAGE DESIGN
FINAL ERROR BUDGET FOR INNER SURFACE MEASUREMENTS

	P-V Magnitude (nm)			
	Without Geometry Compensation		With Geometry Compensation	
	Y	Z	Y	Z
LASER INTERFEROMETERS				
Frequency stability	15.0	30.0	15.0	30.0
Resolution	2.5	2.5	2.5	2.5
Index of refraction	12.5	25.0	12.5	25.0
Optical, electronic factors	5.0	5.0	5.0	5.0
ROTARY TABLE				
Total radial motion (including tilt)	130.0		130.0	
Total axial motion (including tilt)		130.0		130.0
MACHINE GEOMETRY				
Y-slide straightness		500.0		100.0
Lower z-slide straightness	500.0		100.0	
Lower z-slide pitch		250.0		25.0
Squareness				
Lower z-slide to y-slide	250.0	250.0	75.0	75.0
Rotary table to y-slide	250.0	250.0	50.0	50.0
THERMAL EFFECTS				
0.05 degree C gradient--x-direction				
0.05 degree C gradient--y-direction				
0.05 degree C gradient--z-direction		187.5		187.5
0.05 degree C overall change	420.0		420.0	
Rotary table drive motor		75.0		75.0
Part	120.0	120.0	120.0	120.0
LVDT PROBE				
Electronic noise	25.0	25.0	25.0	25.0
Linearity	25.0	25.0	25.0	25.0
PROBE TIP				
Size	18.0	18.0	18.0	18.0
Contour	50.0	50.0	50.0	50.0
GAUGING FORCE	25.0	25.0	25.0	25.0
MASTERING	50.0	50.0	50.0	50.0
DATA ACQUISITION	25.0	25.0	25.0	25.0
Arithmetic Sum: E_A =	1923.0	2043.0	1148.0	1043.0
RMS Sum: *E_R =	221.9	207.9	139.7	91.4
Mean ($(E_A + E_R)/2$): E_M =	1072.5	1125.4	643.8	567.2
Predicted Maximum Error:		E_T = 1.55 µm		E_T = .86 µm
$((E_{MY}^2 + E_{MZ}^2)^{1/2})$				

*Calculations for RMS values assume a uniform probability density for each error about its mean value.

ORIGINAL COP GAGE DESIGN
FINAL ERROR BUDGET FOR OUTER SURFACE MEASUREMENTS

	P-V Magnitude (nm)			
	Without Geometry Compensation		With Geometry Compensation	
	Y	Z	Y	Z
LASER INTERFEROMETERS				
Frequency stability	15.0	22.5	15.0	22.5
Resolution	2.5	2.5	2.5	2.5
Index of refraction	12.5	20.0	12.5	20.0
Optical, electronic factors	5.0	5.0	5.0	5.0
ROTARY TABLE				
Total radial motion (including tilt)	130.0		130.0	
Total axial motion (including tilt)		130.0		130.0
MACHINE GEOMETRY				
Y-slide straightness		500.0		100.0
Upper z-slide straightness	500.0		100.0	
Upper z-slide pitch		250.0		25.0
Squareness				
Upper z-slide to y-slide	250.0	250.0	75.0	75.0
Rotary table to y-slide	250.0	250.0	50.0	50.0
THERMAL EFFECTS				
0.05 degree C gradient--x-direction				
0.05 degree C gradient--y-direction				
0.05 degree C gradient--z-direction	300.0	240.0	300.0	240.0
0.05 degree C overall change				
Rotary table drive motor		75.0		75.0
Part	120.0	120.0	120.0	120.0
LVDT				
Electronic noise	25.0	25.0	25.0	25.0
Linearity	25.0	25.0	25.0	25.0
Thermal stability				
PROBE TIP				
Size	18.0	18.0	18.0	18.0
Contour	50.0	50.0	50.0	50.0
GAUGING FORCE	25.0	25.0	25.0	25.0
MASTERING	50.0	50.0	50.0	50.0
DATA ACQUISITION	25.0	25.0	25.0	25.0
Arithmetic Sum: E_A =	1803.0	2083.0	1028.0	1083.0
RMS Sum: *E_R =	205.0	212.2	110.9	100.8
Mean ($(E_A + E_R)/2$): E_M =	1004.0	1147.6	569.5	591.9
Predicted Maximum Error: $((E_{MY}^2 + E_{MZ}^2)^{1/2})$	E_T = 1.52 µm		E_T = .82 µm	

*Calculations for RMS values assume a uniform probability density for each error about its mean value.

REVISED COP GAGE DESIGN
FINAL ERROR BUDGET FOR INNER SURFACE MEASUREMENTS

		P-V Magnitude (nm)			
		Without Geometry Compensation		With Geometry Compensation	
		Y	Z	Y	Z
LASER INTERFEROMETERS					
Frequency stability		15.0	30.0	15.0	30.0
Resolution		2.5	2.5	2.5	2.5
Index of refraction		12.5	25.0	12.5	25.0
Optical, electronic factors		5.0	5.0	5.0	5.0
ROTARY TABLE					
Total radial motion (including tilt)		130.0		130.0	
Total axial motion (including tilt)			130.0		130.0
MACHINE GEOMETRY					
Y-slide straightness			500.0		100.0
Lower z-slide straightness		500.0		100.0	
Lower z-slide pitch			250.0		25.0
Squareness					
Lower z-slide to y-slide		250.0	250.0	75.0	75.0
Rotary table to y-slide		250.0	250.0	50.0	50.0
THERMAL EFFECTS					
0.05 degree C gradient--x-direction					
0.05 degree C gradient--y-direction					
0.05 degree C gradient--z-direction			187.5		187.5
0.05 degree C overall change		250.0		250.0	
Rotary table drive motor			75.0		75.0
Part		120.0	120.0	120.0	120.0
LVDT PROBE					
Electronic noise		25.0	25.0	25.0	25.0
Linearity		25.0	25.0	25.0	25.0
PROBE TIP					
Size		18.0	18.0	18.0	18.0
Contour		50.0	50.0	50.0	50.0
GAUGING FORCE		25.0	25.0	25.0	25.0
MASTERING		50.0	50.0	50.0	50.0
DATA ACQUISITION		25.0	25.0	25.0	25.0
Arithmetic Sum:	E_A =	1753.0	2043.0	978.0	1043.0
RMS Sum:	*E_R =	199.4	207.9	100.1	91.4
Mean ($(E_A + E_R)/2$):	E_M =	976.2	1125.4	539.0	567.2
Predicted Maximum Error:			E_T = 1.49 µm		E_T = .78 µm
$((E_{MY}^2 + E_{MZ}^2)^{1/2})$					

*Calculations for RMS values assume a uniform probability density for each error about its mean value.

REVISED COP GAGE DESIGN
FINAL ERROR BUDGET FOR OUTER SURFACE MEASUREMENTS

	P-V Magnitude (nm)			
	Without Geometry Compensation		With Geometry Compensation	
	Y	Z	Y	Z
LASER INTERFEROMETERS				
Frequency stability	15.0	22.5	15.0	22.5
Resolution	2.5	2.5	2.5	2.5
Index of refraction	12.5	20.0	12.5	20.0
Optical, electronic factors	5.0	5.0	5.0	5.0
ROTARY TABLE				
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0.05 degree C gradient--y-direction				
0.05 degree C gradient--z-direction	50.0	250.0	50.0	250.0
0.05 degree C overall change				
Rotary table drive motor		75.0		75.0
Part	120.0	120.0	120.0	120.0
LVDT				
Electronic noise	25.0	25.0	25.0	25.0
Linearity	25.0	25.0	25.0	25.0
Thermal stability				
PROBE TIP				
Size	18.0	18.0	18.0	18.0
Contour	50.0	50.0	50.0	50.0
GAUGING FORCE	25.0	25.0	25.0	25.0
MASTERING	50.0	50.0	50.0	50.0
DATA ACQUISITION	25.0	25.0	25.0	25.0
Arithmetic Sum: E_A =	1553.0	2093.0	778.0	1093.0
RMS Sum: *E_R =	186.4	213.3	70.8	102.9
Mean (($E_A + E_R$)/2): E_M =	869.7	1153.2	424.4	598.0
Predicted Maximum Error:		E_T = 1.44 µm		E_T = .73 µm
$((E_{MY}^2 + E_{MZ}^2)^{1/2})$				

*Calculations for RMS values assume a uniform probability density for each error about its mean value

ERROR BUDGET FOR PNEUMO T-BASE LATHE
125mm RADIUS DISC CHECK

	P-U Magnitude (nm) X	Z
Positioning Accuracy		
X-Axis Yaw	250	
Z-Axis Yaw		250
Machine Geometry		
X-Axis Straightness		500
Z-Axis Straightness	250	
Squareness, X to Z	150	150
Probe		
Tip Radius	75	75
Tip Contour	75	75
Deflection	125	125
Disc Accuracy		
Size	125	125
Contour	250	250
Thermal Drift	125	125
Arithmetic Sum:	E_A= 1425	1675
RMS Sum:	E_R= 150	195
Mean ($(E_A + E_R)/2$):	E_M= 788	935

Predicted Maximum Error: $((E_{MX}^2 + E_{MZ}^2)^{1/2})$ $E_T = 1.22\ \mu m$

Accuracy as tested: $E_D = 1.2\ \mu m$

Accuracy testing of the COP Gage will be completed in 1991.

A comparison between predicted and measured contouring accuracy values will be reported at that time.