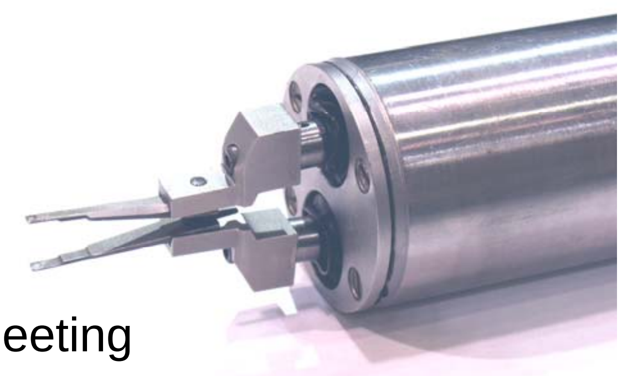
Bore Waviness Recognition Using an In-Process Gage

Project Update

Kristian Krueger

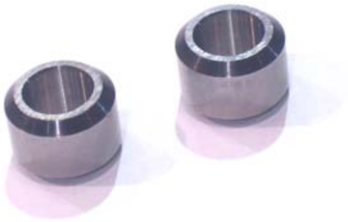


Industrial Advisory Board Meeting

October 20, 2004

Problem Statement

- Valve tappets can irregularly exhibit waviness after grinding of the bore
- Sample parts are taken from the manufacturing process and tested for waviness
- Currently, if waviness is detected the entire lot is inspected manually
  - Significant costs in terms of time and money
  - Low repeatability of the manual inspection



Research Objectives

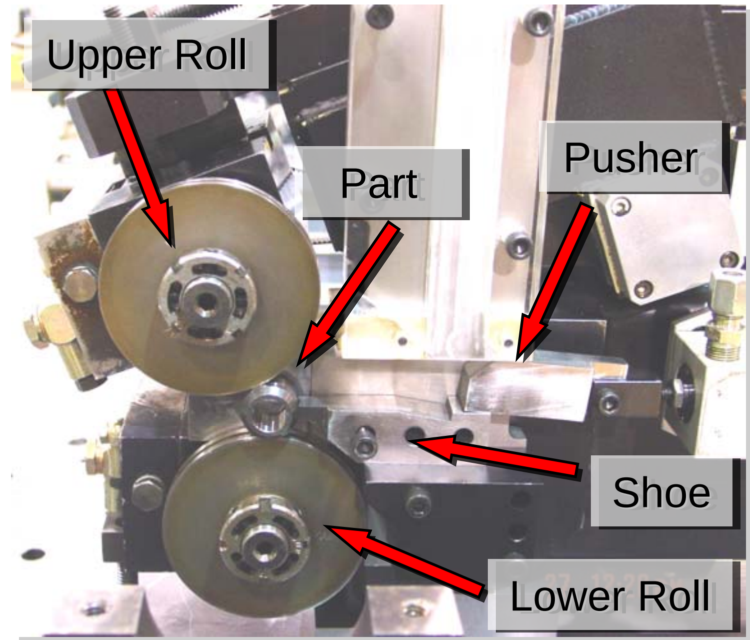
- Objective 1
  - Develop a prototype machine that is capable of automatic waviness detection. The machine can be used as a post-process machine to sort out parts with waviness.

- Objective 2
  - Evaluate the possibilities and limitations to implement the waviness detection directly in the grinding machine.

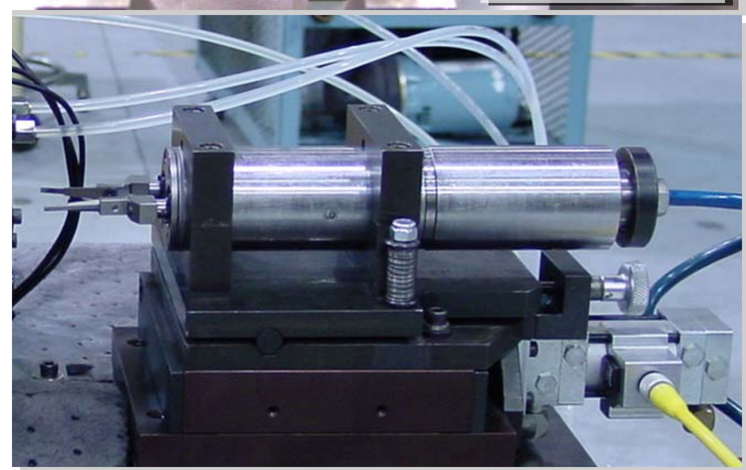
The prototype machine will be built using the same fixture and the same measurement system already present in the grinding machine.

Key Machine Components

- Roll-Shoe Centerless Fixture
  - Prototype of the fixture used in the grinding machine
  - Part position is defined by two rolls and a shoe
  - Hydrostatic bearings for roll spindles
  - Pusher and upper roll actuated by hydraulic cylinders

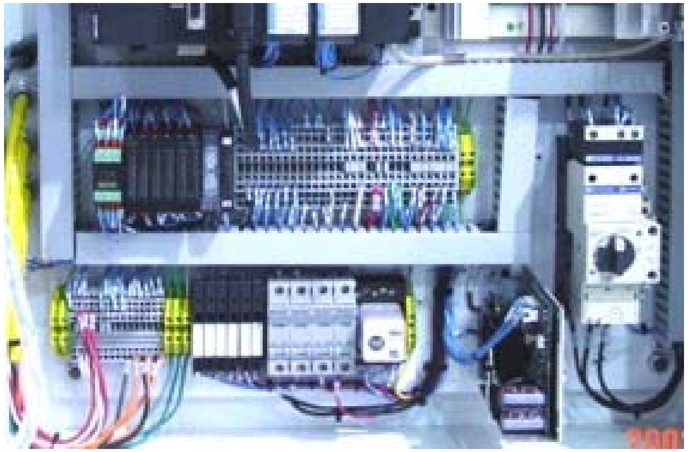


- Marposs Thruvar 5 Gage Head
  - Two diamond tipped fingers that trace the inner diameter of the part
  - Two LVDTs to convert finger displacement into electrical signal

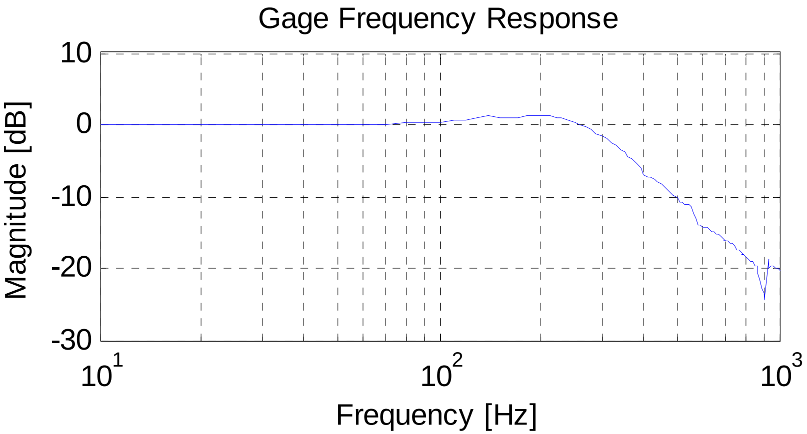


Sources of Inaccuracies

- Electrical Noise
  - EMI/RFI, magnetic fields
  - Fluctuation of power supply voltages
  - Ground loops



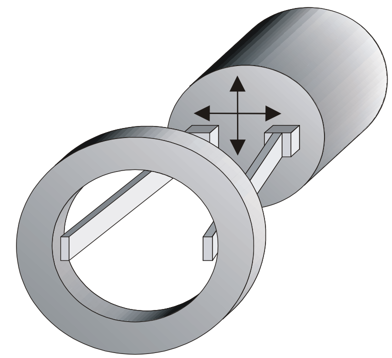
- Cutoff Frequency of the Gage Head
  - -3dB cutoff frequency is 330 Hz
  - To measure waviness up to 300 upr the part rotational speed can be 1 rev/sec
  - To measure waviness up to 300 upr in a grinding machine a cutoff frequency of 4.5 kHz is required



Sources of Inaccuracies

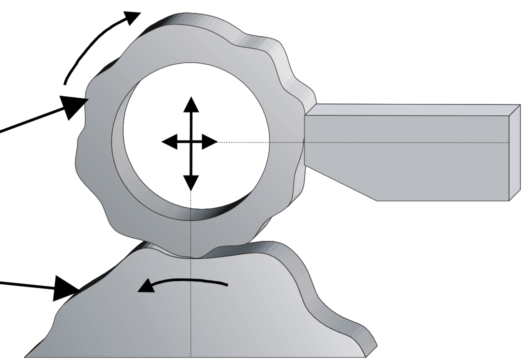
- Forced Vibrations

  (movement between gage and fixture)
  - Pulsation of hydraulic fluid
  - Roll motor
  - Environment
  - Grinding wheel (in the grinding machine)



- Centerless Fixture

  (movement between part center and fixture)
  - Roundness error of the part outer diameter
  - Roundness error of the rolls



- Additional Disturbances in the Grinding Machine
  - Effect of coolant and swarf

Accuracy Improvement

Type	Source	Prototype Machine	Grinding Machine
Mainly random	Electrical Noise	Shielding, grounding and cabling techniques ✓	
	Electrical Noise / Forced Vibrations	Averaging over multiple measurements ✓	
	Forced Vibrations	Low vibration motor drive ✓	
	Forced Vibrations	Vibration isolation system ✓	
	Forced Vibrations	Hydraulic accumulators ✓	
	Forced Vibrations / Centerless Fixture	Separation of vibration from part profile	
	Centerless Fixture	Roll eccentricity filter ✓	
Mainly deterministic	Gage Cutoff	Low part rotational speed ✓	Attenuation Compensation ✓

☐ = technical method ☐ = analytical method ✓ = implemented methods

Reduction of Electrical Noise

- Careful grounding to prevent ground loops
- Shielding of signal conditioning card
  - Design of a shielded enclosure for protection against electric fields, magnetic fields and EMI/RFI
- Gain Selection
  - Optimization of the gage and signal conditioning card gains to minimize noise
- Use of double shielded cables
- Results of noise reduction
  - Standard deviations

	[μinch]	[nm]
Finger A	0.41	10.3
Finger B	0.25	6.3

Comparison to Roundness Machine

- Procedure
  - 120 test parts (mixture between good and bad parts)
  - 5 measurements per part on a roundness machine at slightly different axial positions (0.25 mm axial spacing)
  - 2 measurements per part on the prototype machine

Roundness Machine

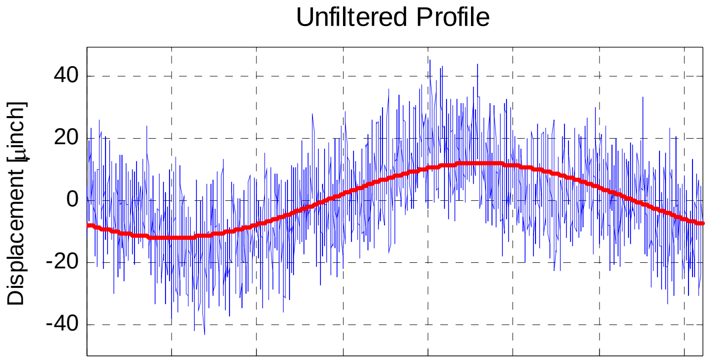
- Results

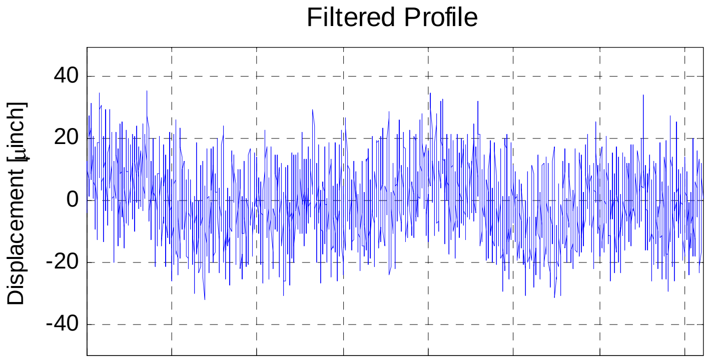
Roundness Machine		Prototype Machine: good	Prototype Machine: good/bad	Prototype Machine: bad
good:	36 (100%)	31 (86.1%)	3 (8.3%)	2 (5.6%)
good/bad:	30 (100%)	2 (6.7%)	3 (10.0%)	25 (83.3%)
bad:	54 (100%)	0 (0.0%)	0 (0.0%)	54 (100.0%)

- 100% of all bad parts are detected as bad parts
- 86.1% of all good parts are detected as good parts

Roll Eccentricity Filter

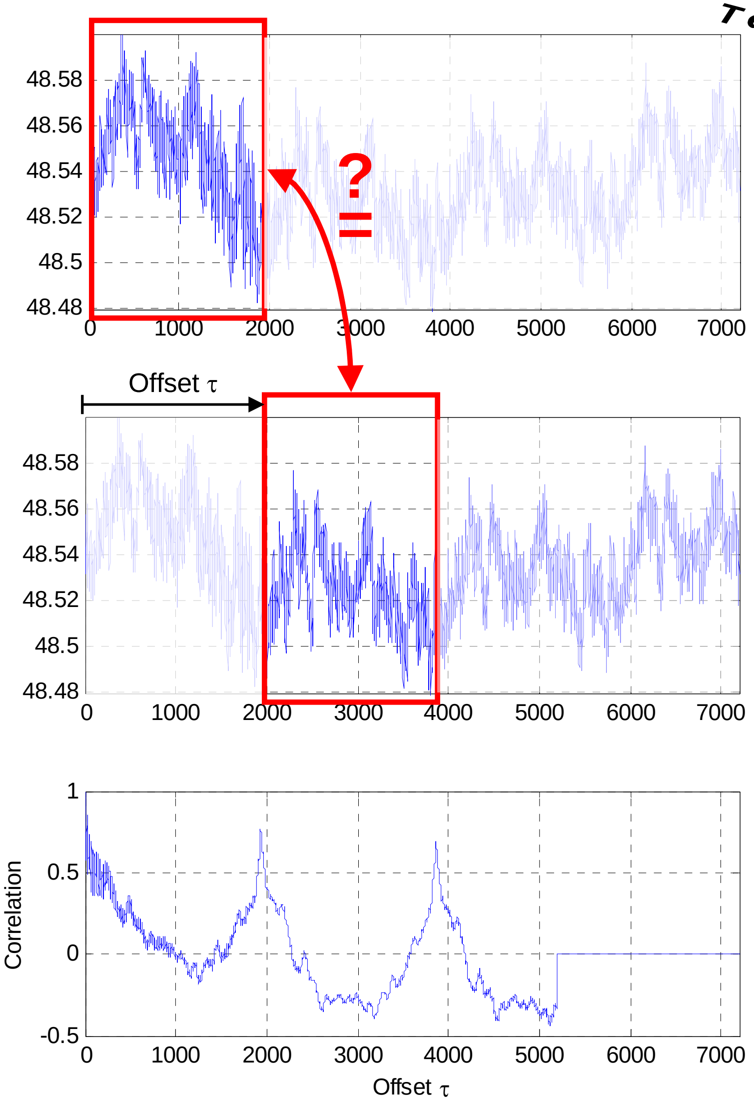
- Procedure
  - Least squares fit of a sine wave with the same frequency as the roll revolution to the profile
  - Subtracting the sine wave from the profile yields the filtered profile
  - Sine wave can be fitted to profile of any length





Averaging of Measurements

- Problem
  - Data acquisition is triggered by an encoder on the motor spindle
  - number of data points per workpiece revolution is not constant
- Method
  - Compare different segments of the measurement to detect when profile repeats itself
  - Correlation coefficient is used to quantify similarity of segments
  - Profiles are averaged in the frequency domain
- Assumption
  - Profile does not change during measurements

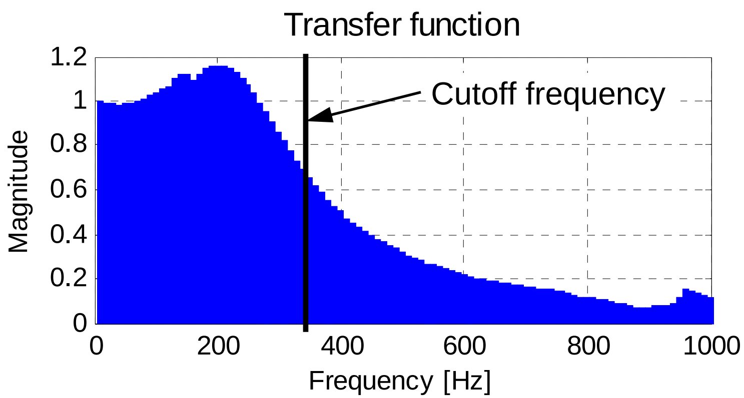


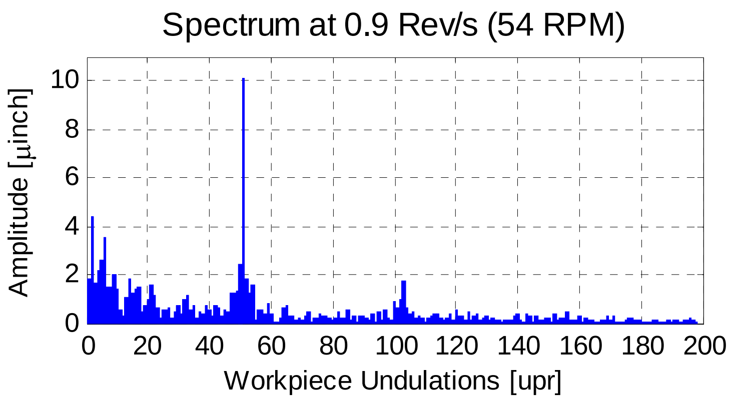
Gage Cut-off Compensation

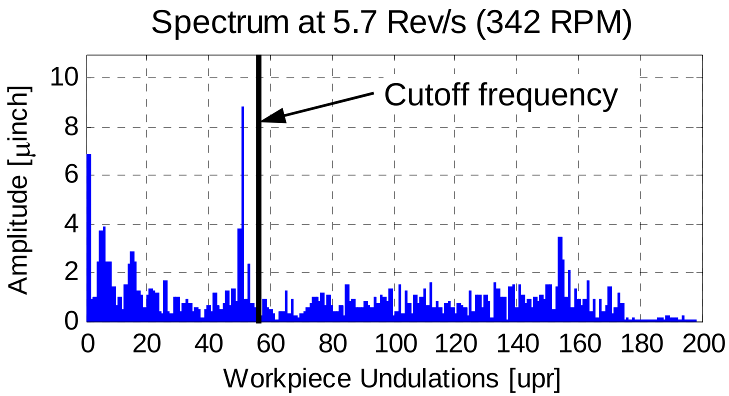
❖ Method

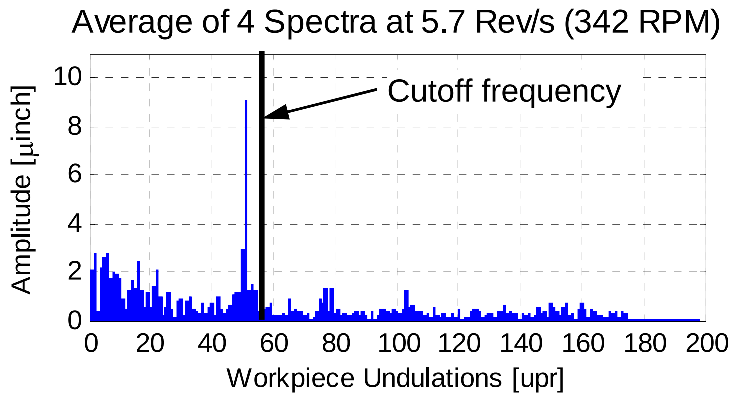
– Spectrum is multiplied by the inverse of the transfer function to restore original amplitudes and phases

– Since noise is amplified, spectrum is averaged over multiple measurements



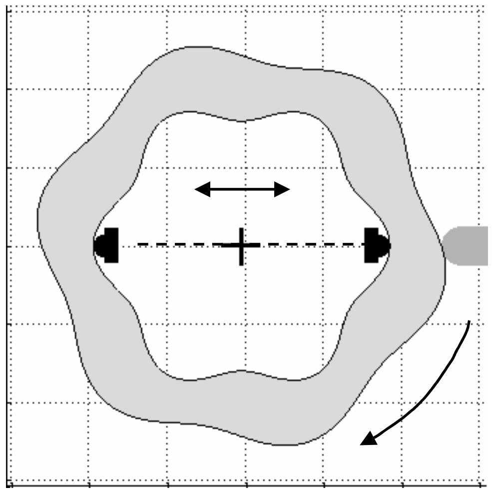






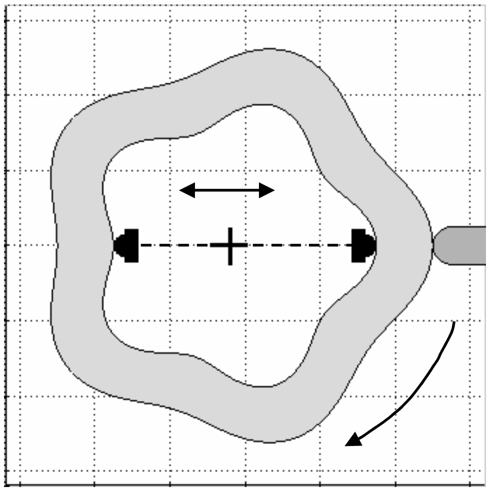
Vibration Separation

- Vibration Separation
  - Two fingers measure the same profile
  - Can redundant information be used to separate vibration from profile information?



6 Lobes on ID and OD

- Example: Part with 5 lobes
  - Displacement of both fingers will always be constant
  - Waviness cannot be detected with this configuration
  - With this configuration vibration can only be separated for even lobes

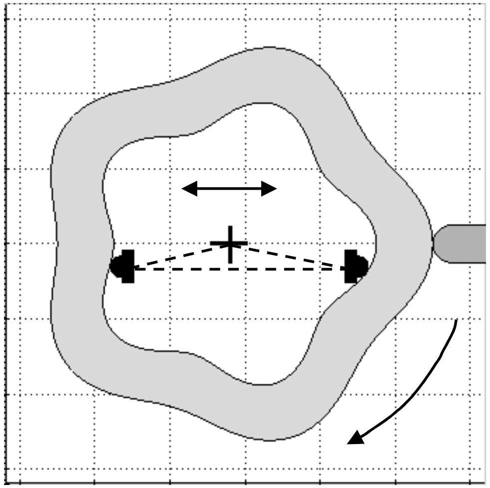


5 Lobes on ID and OD

- Literature Review
  - Usually 3 [*Gao, Kiyono 1997*] or 4 fingers [*Zhang, Wang 1992*] used for vibration separation

Vibration Separation

- Solution
  - Place fingers slightly eccentrically
  - Separation theoretically possible for even and odd lobes
  - For a certain range of lobes an optimal finger angle can be determined for vibration separation



5 Lobes on ID and OD

- Requirements
  - Effect of vertical vibration on finger signal must be negligible
  - Workpiece must not deform
  - Finger angle must be known
    - Seek for an analytical method to determine finger angle from measured profiles

Future Work

- New measurement series and comparison to roundness machine
  - New measurement series that reflects the latest technical improvements of the post-process machine
- Development and Refinement of Analytical Methods
  - Refinement of averaging and cutoff compensation
  - Development of analytical methods for vibration separation
- Measurement series on the Grinding Machine
  - Estimation of the achievable accuracy
  - Highest possible rpm for waviness detection
  - Possibility for removal of vibration
- Statistical analysis of the measurement results
  - Estimation of errors and confidence intervals on the measurement

Additional Slides

Part Specifications

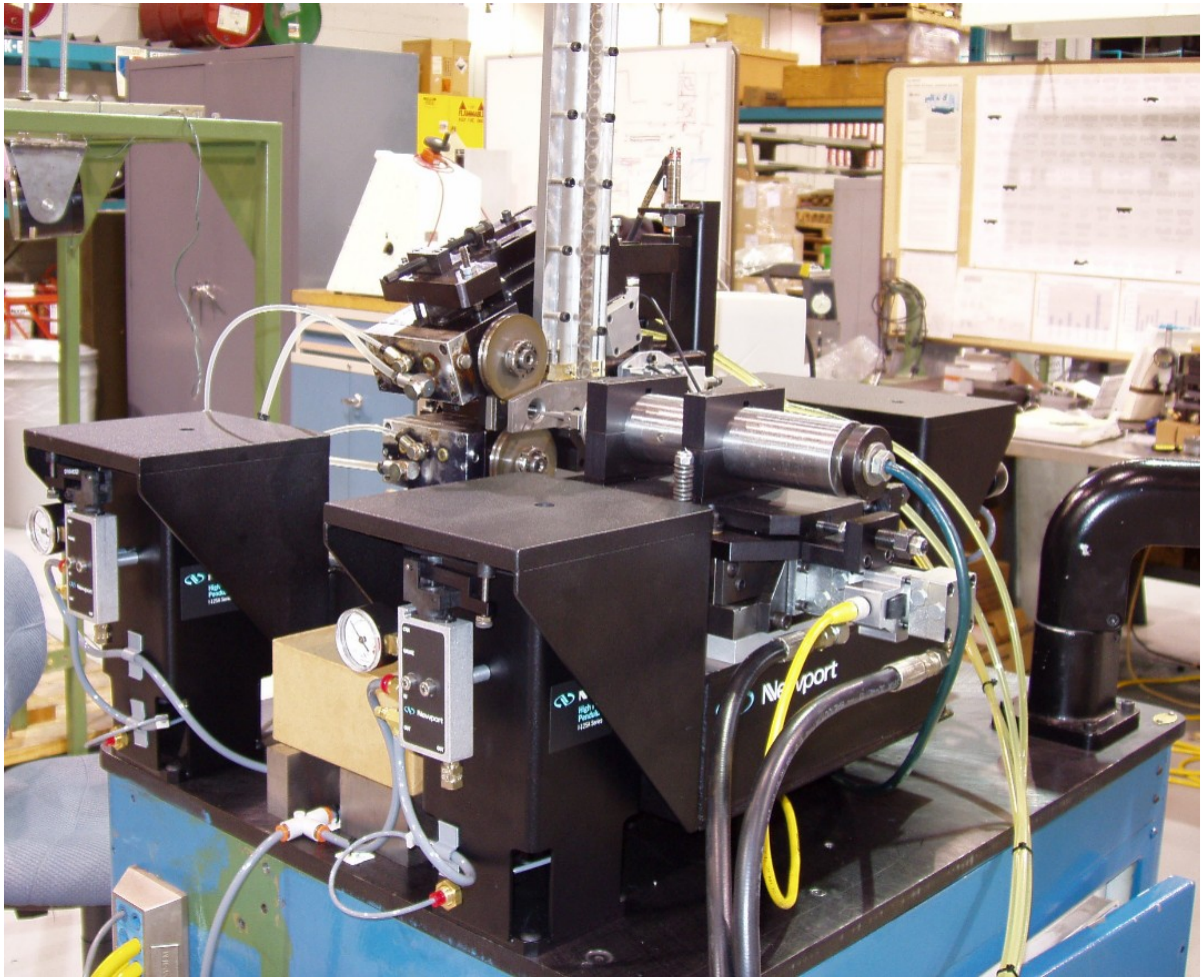
- Definition of waviness according to company specification TPS 2100

- Two Definitions
  - Any lobing pattern which occurs 10 to 250 times around the full circumference

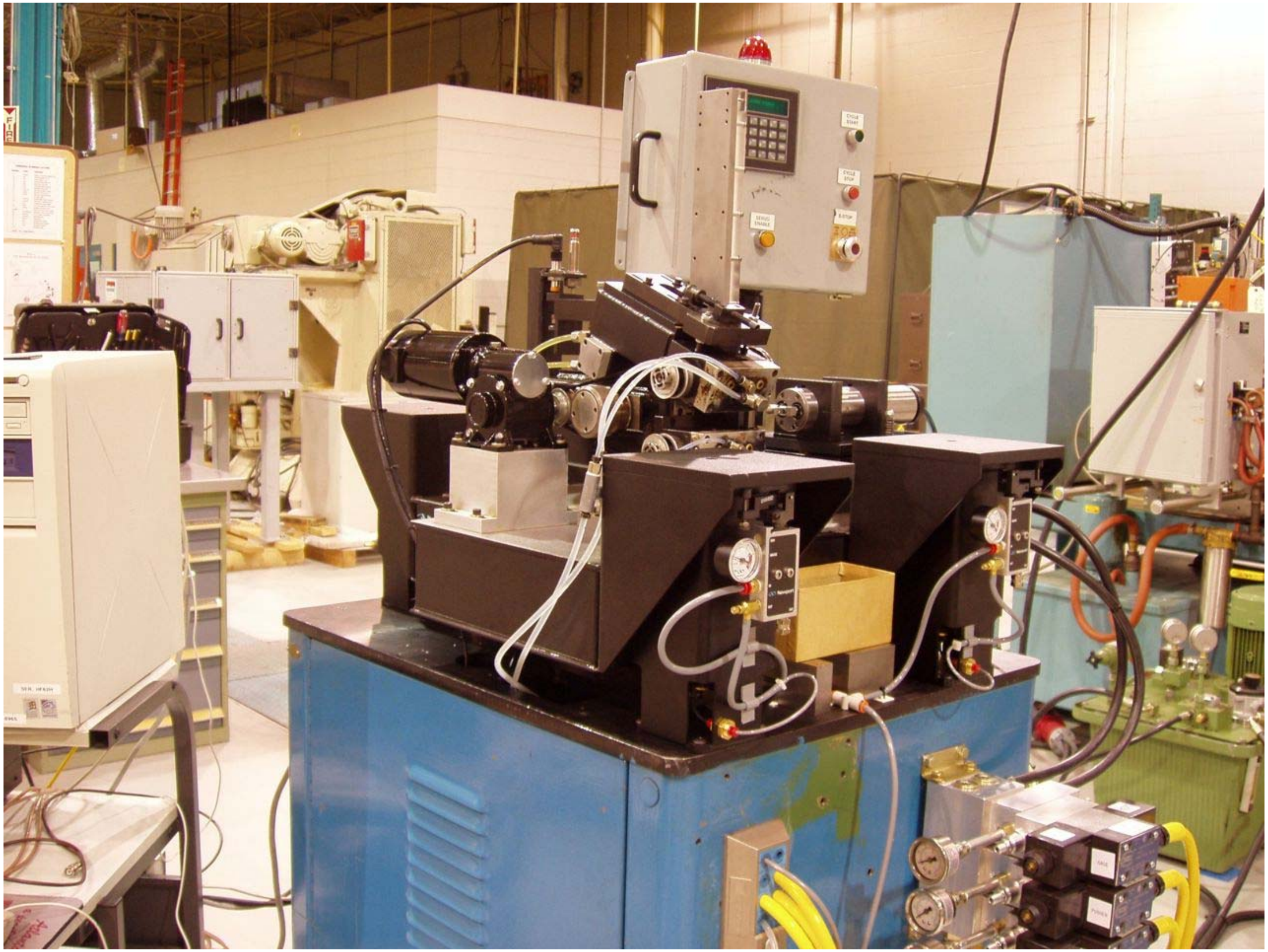
    or
  - Any lobing pattern which occurs 2 to 50 times around any 60 degree arc

- Criterion
  - The allowable waviness height for both cases is 50 μinch

Post Process Machine

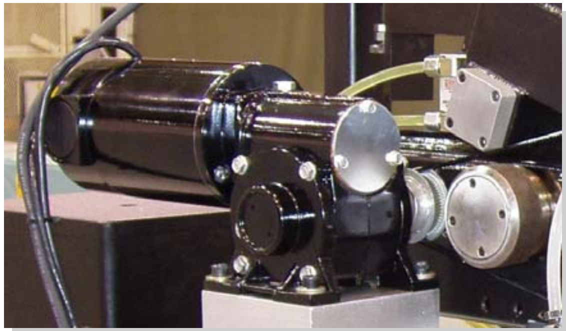


Post Process Machine

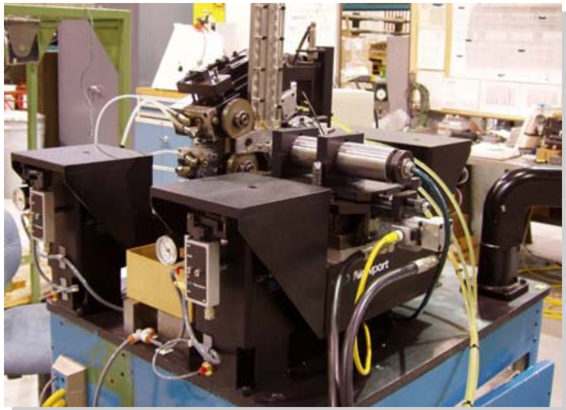


Reduction of Forced Vibrations

- Low Vibration Roll Motor Drive
  - With original drive roll motor introduced vibration at 120 Hz
  - New motor drive provides a very smooth rotation and eliminates 120 Hz vibration



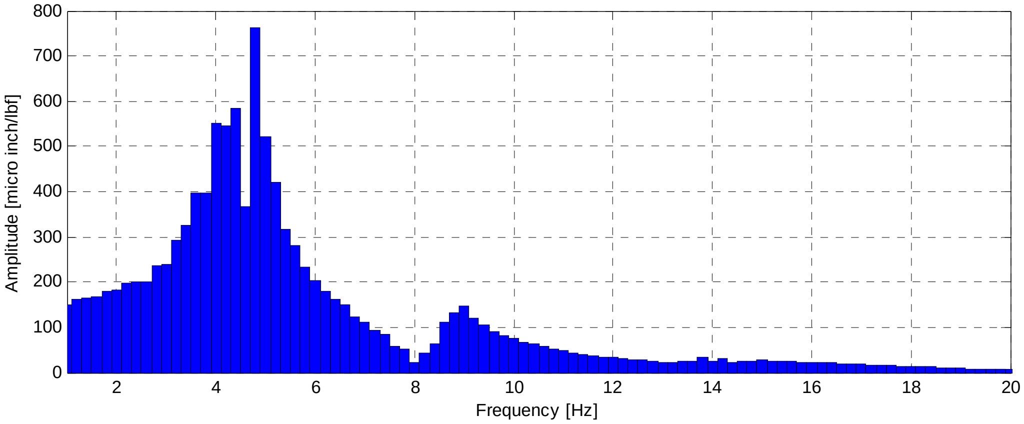
- Vibration Isolation System
  - Components mounted on a 4 inch thick Honeycomb plate for high stiffness
  - Components and plate are supported by 4 pneumatic isolators which attenuate vibration above 10 Hz



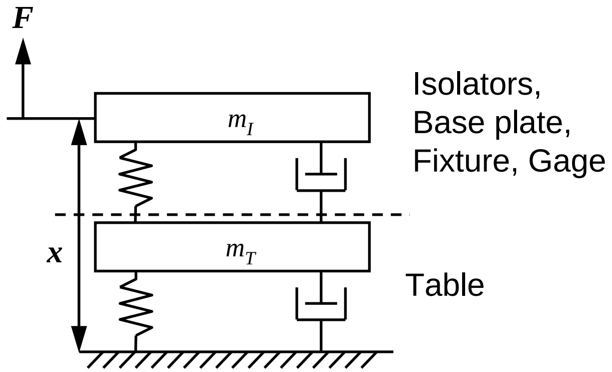
- Hydraulic accumulators
  - Two 0.32 liters pulsation dampeners to reduce vibration from hydraulic fluid

Vibration Isolation System

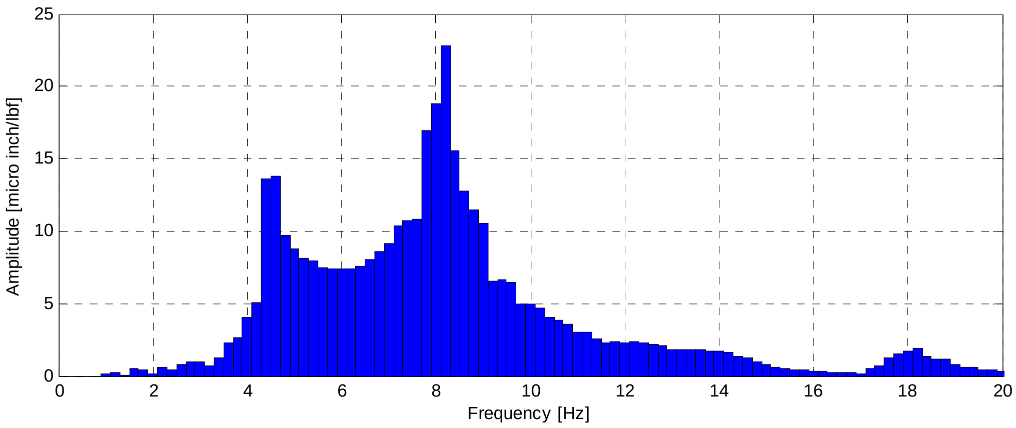
– Frequency response

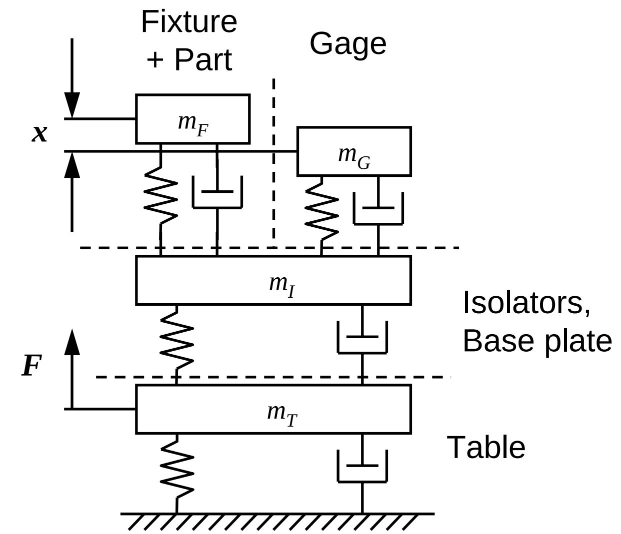


Equivalent 1 DOF-system



– Susceptibility of the measurement to vibration





Comparison to Roundness Machine

- Modified Procedure
  - Only one measurement per part
  - But second measurement of the part immediately after the first measurement if waviness height falls between 50 and 60 μinch.
  - Accept the part if it passes the second test.

Roundness Machine

- Results

Roundness Machine		Prototype Machine: good	Prototype Machine: good/bad	Prototype Machine: bad
good:	36 (100%)	34 (94.4%)	0 (0.0%)	2 (5.6%)
good/bad:	30 (100%)	5 (16.7%)	0 (0.0%)	25 (83.3%)
bad:	54 (100%)	0 (0.0%)	0 (0.0%)	54 (100.0%)

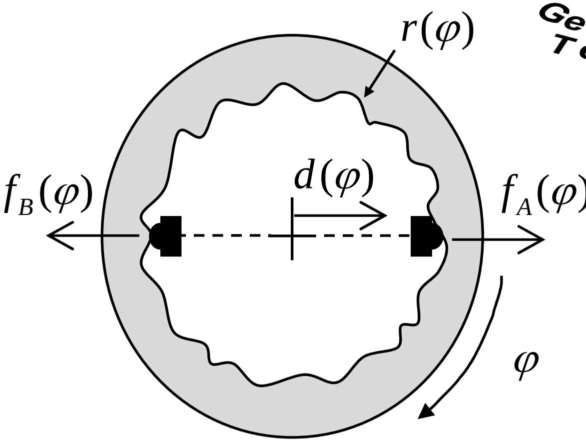
  - Now 94.4% of all good parts are detected as good parts
  - Still 100% of bad parts are detected as bad parts

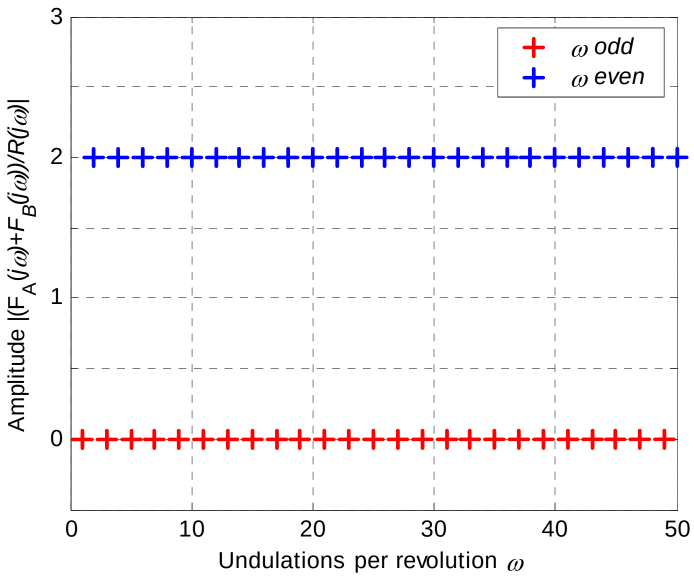
Vibration Separation

- Input Variables
  - Profile $r(\varphi)$
  - Displacement relative to gage $d(\varphi)$
- Measured Finger Signals
  - Finger A $f_A(\varphi) = r(\varphi) + d(\varphi)$
  - Finger B $f_B(\varphi) = r(\varphi - \pi) - d(\varphi)$
  - Sum A+B $f_A(\varphi) + f_B(\varphi) = r(\varphi) + r(\varphi - \pi)$
- Transfer function of A+B

$$\frac{F_A(j\omega) + F_B(j\omega)}{R(j\omega)} = 1 + e^{-\pi\omega j}$$

- Odd frequencies cannot be separated





Vibration Separation

- Angle less than 180º

  Finger angle β

- Measured Finger Signals

$$f_A(\varphi) = r(\varphi)\cos(\beta/2) + d(\varphi)$$

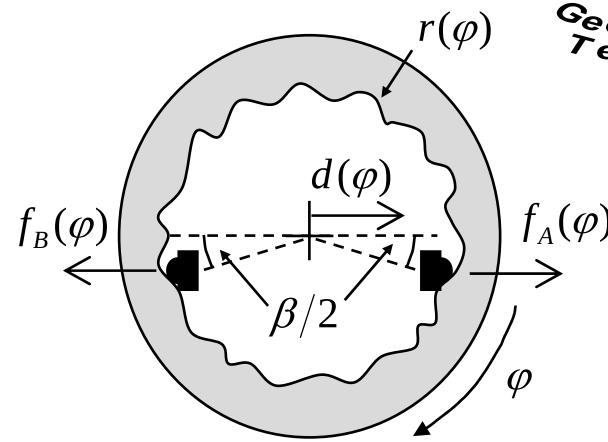
$$f_B(\varphi) = r(\varphi - \pi + \beta)\cos(\beta/2) - d(\varphi)$$

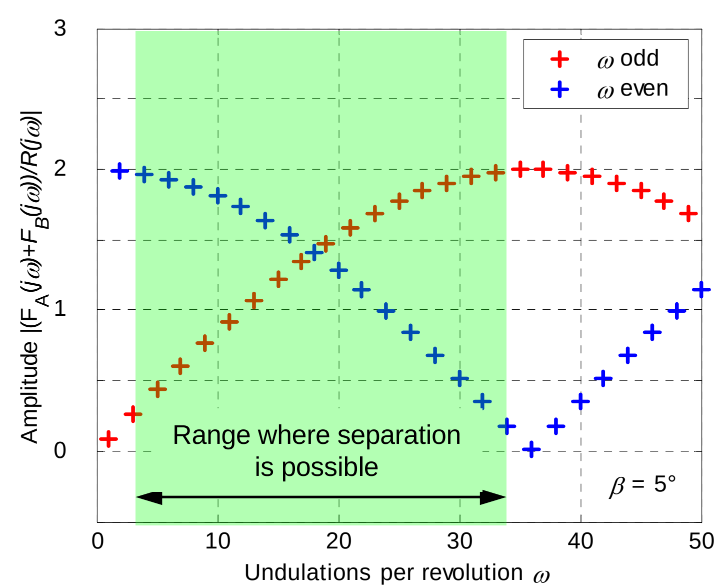
$$f_A(\varphi) + f_B(\varphi) = \big(r(\varphi) + r(\varphi - \pi + \beta)\big)\cos(\beta/2)$$

- Transfer function of A+B

$$\frac{F_A(j\omega) + F_B(j\omega)}{R(j\omega)} = \left(1 + e^{-(\pi-\beta)\omega j}\right)\cos(\beta/2)$$

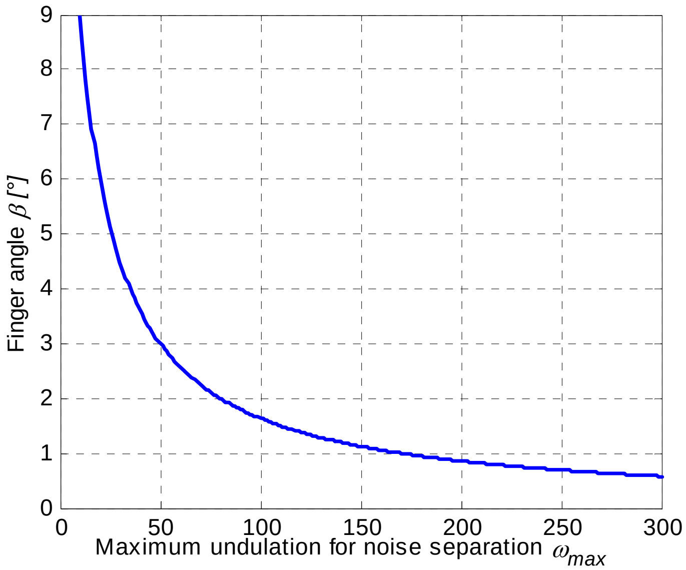
- All frequencies may be separable





Vibration Separation

Optimal finger angle β to filter undulations from 10 to ω_{max}



Limitations/Difficulties

- Exact angle between fingers not known or not repeatable
- Workpiece slipping
- Effect of vertical vibration of the workpiece
- Random noise

Model of the workpiece in the fixture that incorporates these factors and allows statement about the accuracy of the vibration separation method

Experimental Results

Configuration with β=0º (separation for even lobes only)

Measurement of a part with chatter at 32 UPR

Machine excited by an impulse during measurement

Filtering of the vibration