부산대학교
PUSAN NATIONAL UNIVERSITY

AMOI
Advanced Manufacturing & Optical Instrumentation Lab

Advanced Manufacturing & Optical Instrumentation Lab.

첨단생산 및 광계측 실험실

Pusan National University
School of Mechanical Engineering
Prof. Yangjin Kim

Principal Investigator

AMOI
Advanced Manufacturing & Optical Instrumentation Lab

Prof. Yangjin Kim, PhD

Education

- **The University of Tokyo** — 04/2012 – 03/2015
  PhD in Mechanical Engineering
- **The University of Tokyo** — 04/2007 – 03/2009
  MS in Mechanical Engineering
- **The University of Tokyo** — 04/2003 – 03/2007
  BS in Mechanical Engineering

Experience

- **Pusan National University** — 09/2020 – Current
  Associate Professor, School of Mechanical Engineering
- **The University of Tokyo** — 03/2024 – 02/2025
  Associate Professor, Department of Mechanical Engineering
- **Pusan National University** — 09/2016 – 08/2020
  Assistant Professor, School of Mechanical Engineering
- **The University of Tokyo** — 02/2016 – 08/2016
  Assistant Professor, Department of Mechanical Engineering
- **The University of Tokyo** — 04/2015 – 01/2016
  Postdoctoral Researcher, Department of Mechanical Engineering
- **Korea Institute of Machinery and Materials** — 02/2009 – 03/2012
  Technical Research Personnel (Military Service)

Research Outline

AMOI
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Precision Measurement

Phase extraction from fringe patterns

- Traditional phase shifting
- Iterative method
- Machine learning (deep learning)

Measurement of optical devices

- Surface topography
- Thickness (absolute, variation)
- Refractive index (reflectivity)
- Simultaneous measurement
- Absolute radius

Machine Tool

FEA modeling of machine tool

- Modeling of machine tool joints
- Stiffness tuning of machine tool joints
- Volumetric error compensation

Structural/thermal analysis

- Rib structure of bed and column
- Spindle of steel composites
- Turning center turret of CFRP
- Applications of new materials to frame of machine tools

Conference

Domestic conference

KSPE
사단법인 한국정밀공학회
Korean Society for Precision Engineering

KSME
사단법인 대한기계학회
The Korean Society of Mechanical Engineers

KSMTE
한국생산제조학회

International conference

SPIE.

ASPEN

PE
American Society for
Precision Engineering

PRESM

Precision Measurement using Optical Interferometry

Semiconductor Lithography Equipment

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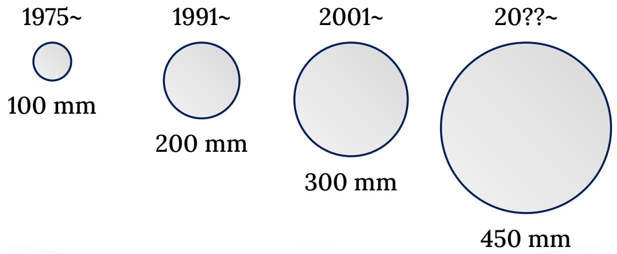
Semiconductor industry

1. Low cost
2. Mass Production
3. Miniaturized circuit of chip

- Large diameter of wafer



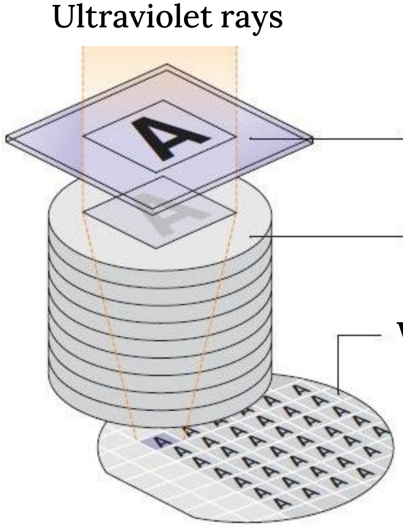
Large diameter of blank mask

- Wavelength

Optical Mask (transmission)
i-Line(365 nm)
KrF(248 nm)
ArF(193 nm)

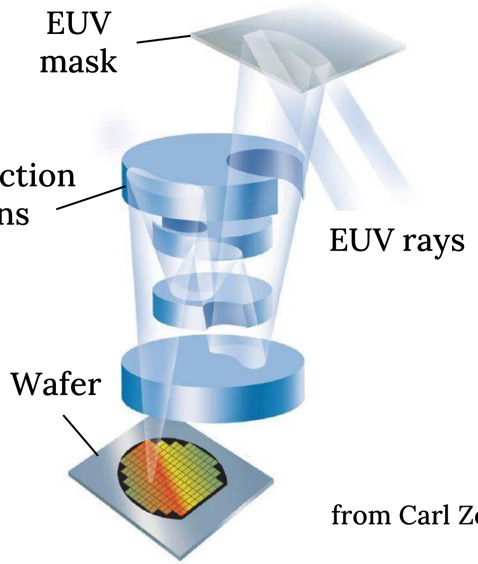
EUV Mask (reflection)
EUV (13.5 nm)

Optical lithography



from TOPPAN

EUV lithography



from Carl Zeiss

	2023	2024	2025	2026	2027
Optical mask substrate flatness [nm]	37	33	29	26	24
EUV mask substrate flatness [nm]	11	10	9	8	7
EUV mask substrate flatness metrology uncertainty [nm 3σ]	2.2	2.0	1.9	1.8	1.7

from 2020 IRDS

Precise measurement of transparent plate and lens
(surface shape, thickness, refractive index...)

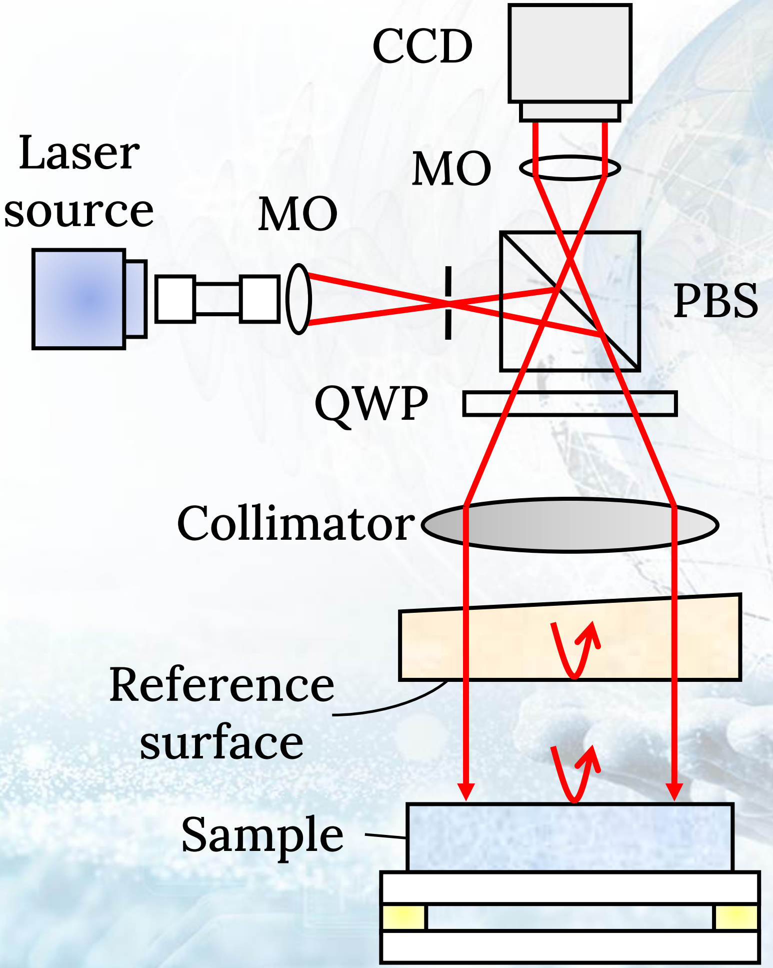
Ideal Measurement System

- High accuracy (excellent measurement uncertainty)
- Low cost (large-aperture measurement)
- Non-contact testing
- Simultaneous measurement (thickness & surface shape...)
- Complex surface

Wavelength tuning Fizeau interferometry

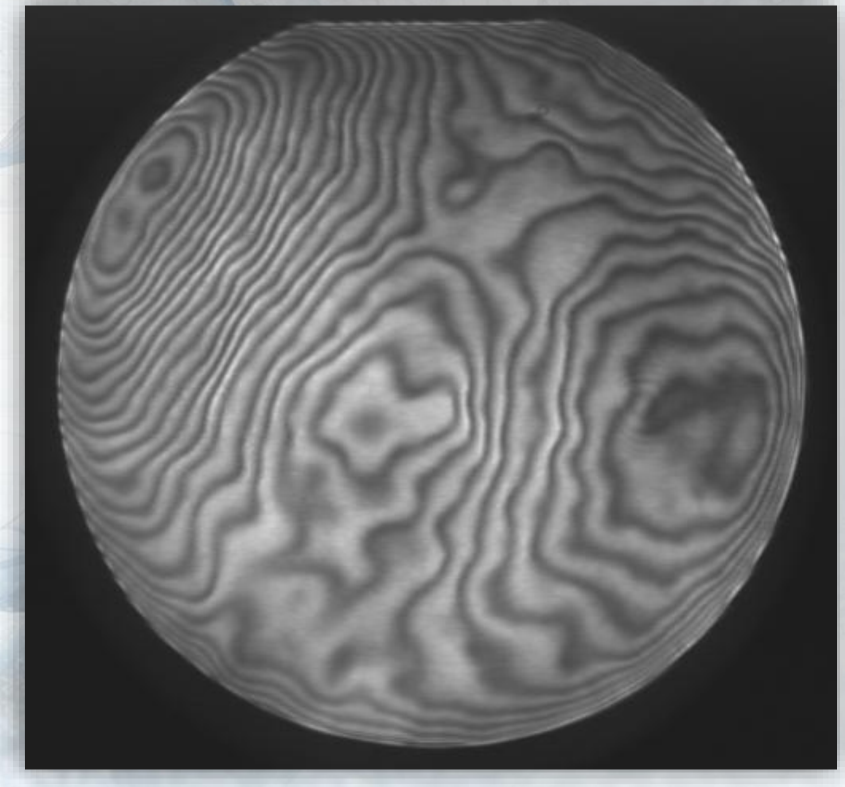
- Fizeau interferometer
- Phase extraction from the observed interferograms

Fizeau Interferometer



- MO: microscope objective
- PBS: polarized beam splitter
- QWP: quarter-wave plate

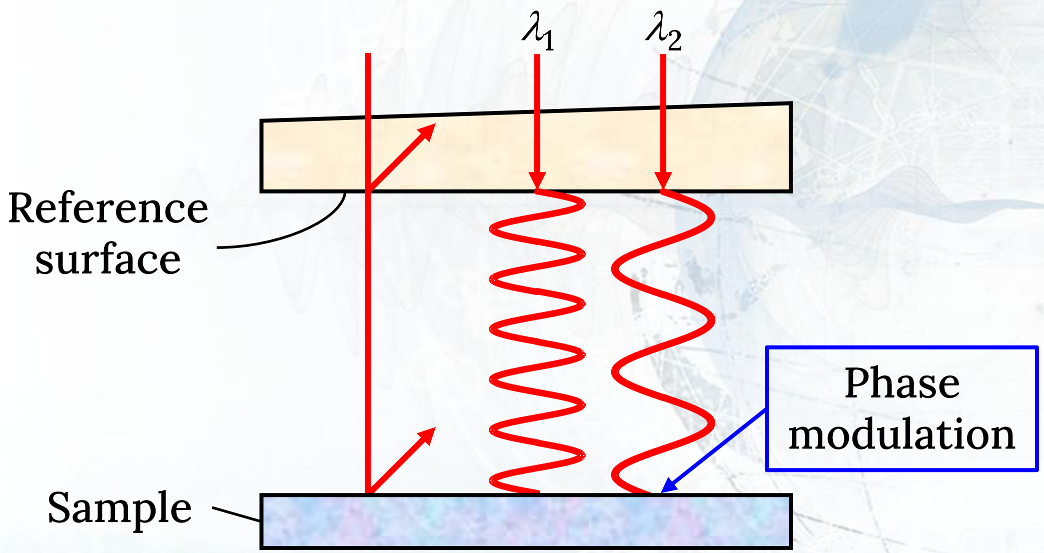
- Interferogram (sample: silicon wafer)



- Less susceptible to air disturbance
- Easy to extend to the measurement of large-aperture sample

Wavelength Tuning Interferometry

- Wavelength tuning from λ_1 to λ_2 ($\lambda_1 < \lambda_2$)

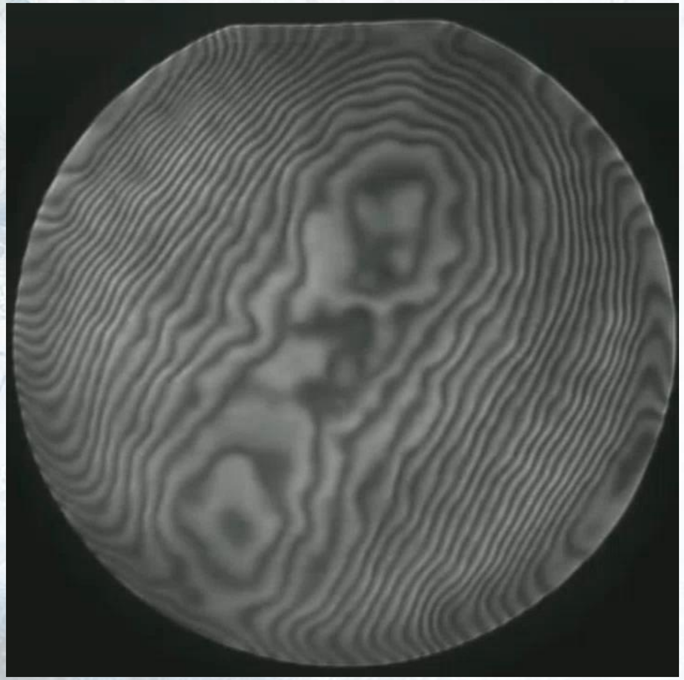


- Intensity during wavelength tuning

$$I(\alpha_r) = I_0 + I_1 \cos(\alpha_r - \varphi)$$

$I(\alpha_r)$: intensity of the rth image
I_0 : intensity of DC component
I_1 : intensity of fundamental signal
r : sampling number
α_r : phase-shift parameter
φ : target phase (phase of surface shape)

- Interferogram



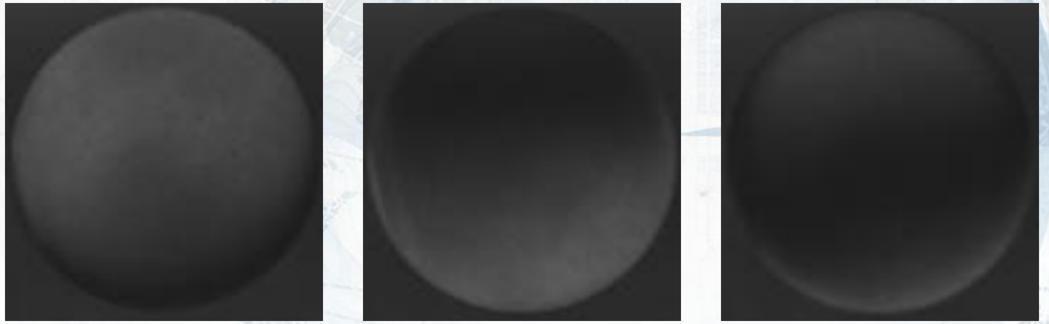
- Image acquisitions during wavelength tuning
- Calculation of phase φ

✓ Surface shape
✓ Optical thickness variation

Phase Extraction from Interferograms

$I(\alpha_r) = I_0\left[1 + \gamma \cos(\alpha_r + \varphi)\right]$

3 variables → Minimum **3** interferograms



Phase Extraction φ (calculation)

Phase-shifting technique

- Fringe patterns (~ 50)
- Environmental uncertainties
- Commercialized (ZYGO)

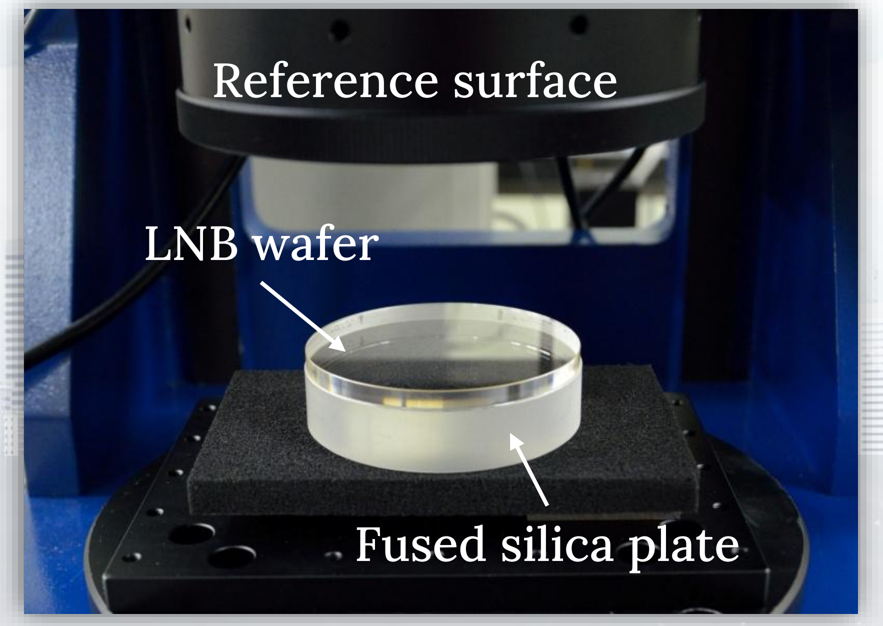
Iterative method

- Fringe patterns (~ 10)
- Error from singular matrix
- Not commercialized

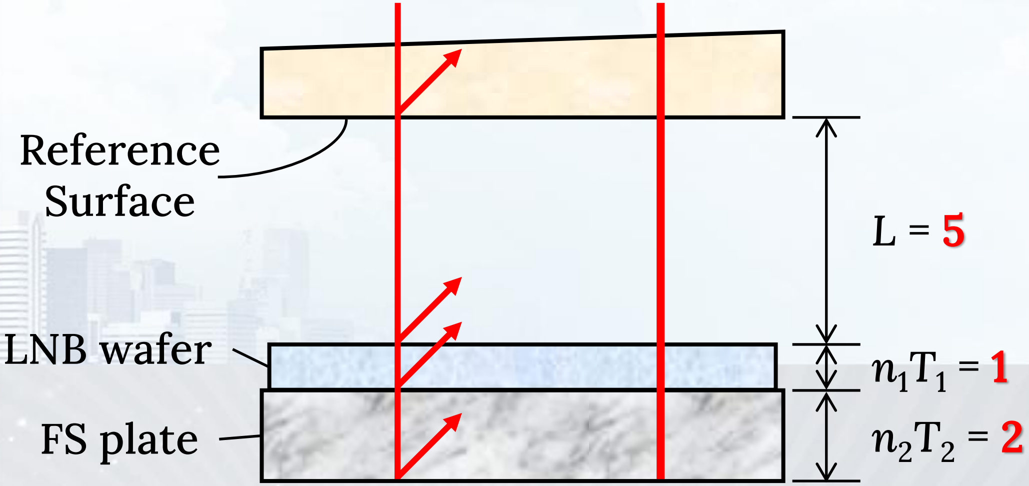
Machine learning

- Fringe patterns (only 2)
- Great accuracy
- Not commercialized

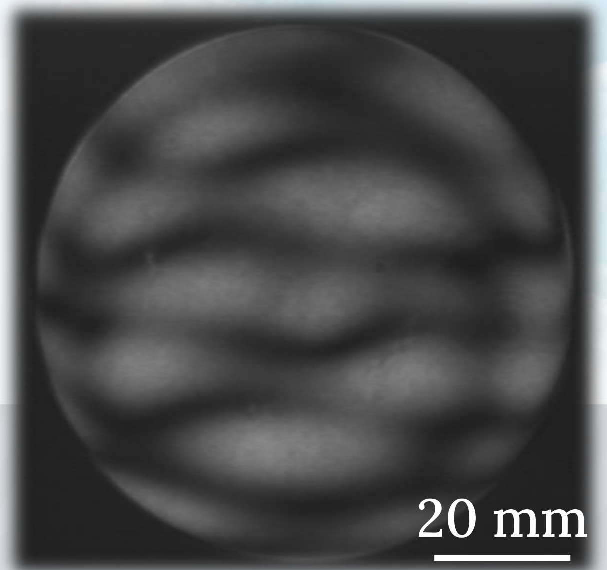
Application 1 : Multi-Layer Interferometry



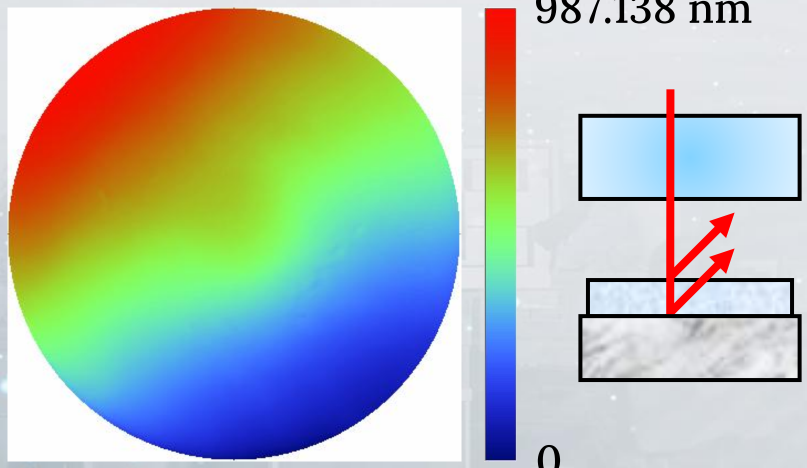
- 6 different fringe patterns ($_4C_2 = 6$)



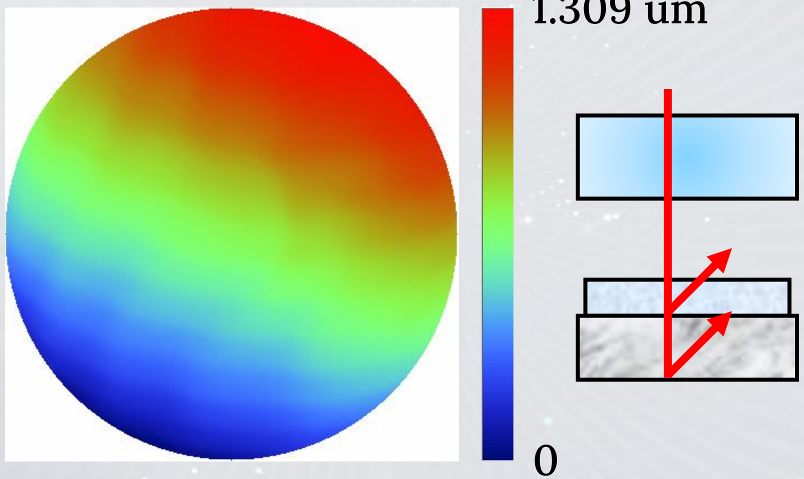
Raw interferogram



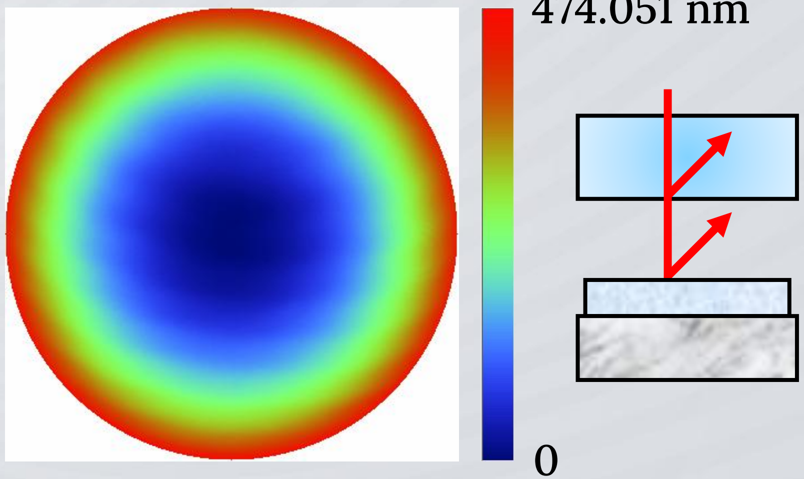
- Thickness (LNB)



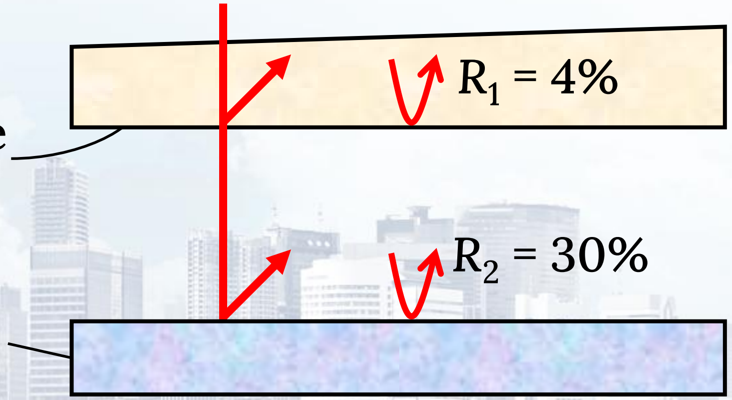
- Thickness (FS)



- Surface (LNB)

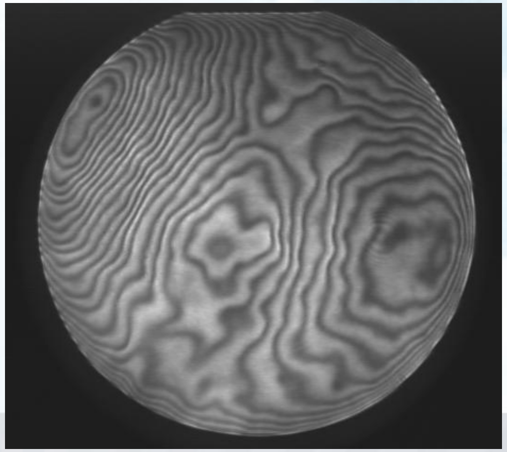


Application 2 : Surface Topography of Wafer



Reflectivity: 30%

Raw interferogram



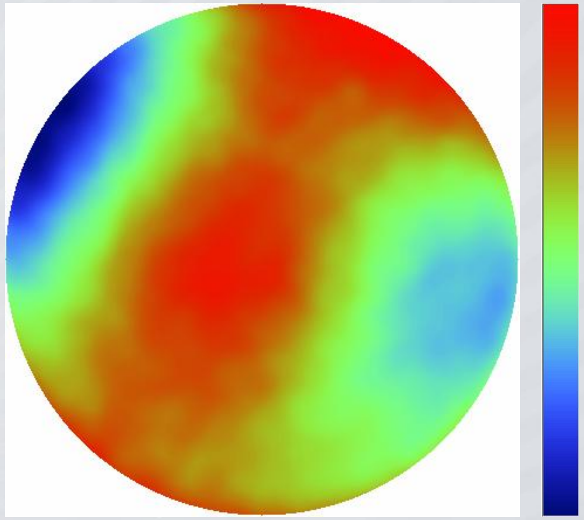
- Intensity of fringe pattern

$$I(\alpha_r) = I_0 + I_0\gamma_1\cos(\varphi_1 - \alpha_r) + I_0\gamma_2\cos(\varphi_2 - 2\alpha_r) + I_0\gamma_3\cos(\varphi_3 - 3\alpha_r)\cdots$$

Fundamental signal | 2nd harmonic signal | 3rd harmonic signal

<u>Coupling error</u> between *harmonics* and *phase-shift error*

4N – 3 phase-shifting algorithm

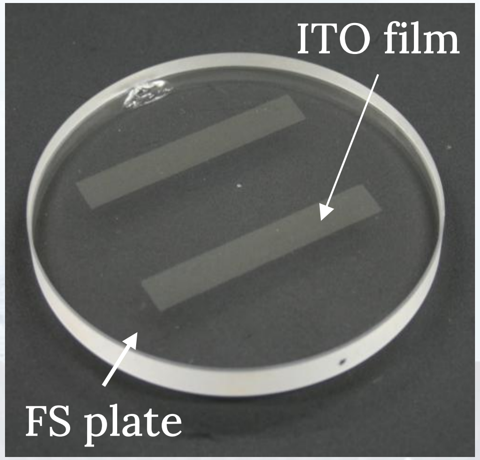


Measurement accuracy: 2.2 nm

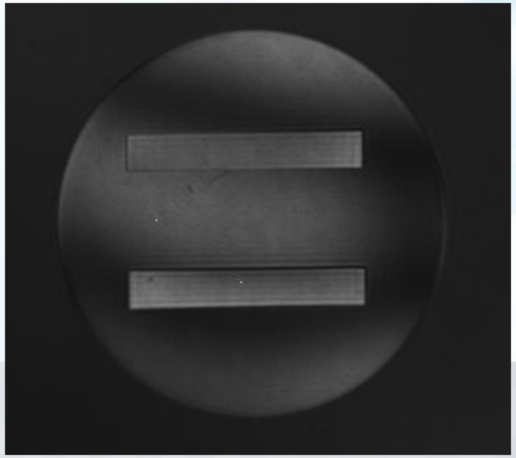
Application 3 : Thickness Profiling of ITO Film

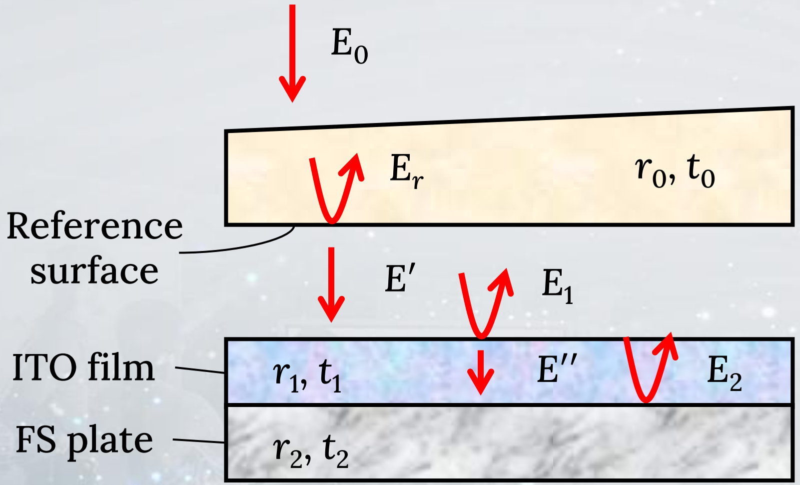
- Indium Tin Oxide thin film (ITO film)
  - Favorable electrical conductivity
  - Optical transparency

Transparent conducting film in
- ✓ display
- ✓ organic light-emitting diode (OLED)
- ✓ solar cell



Raw interferogram





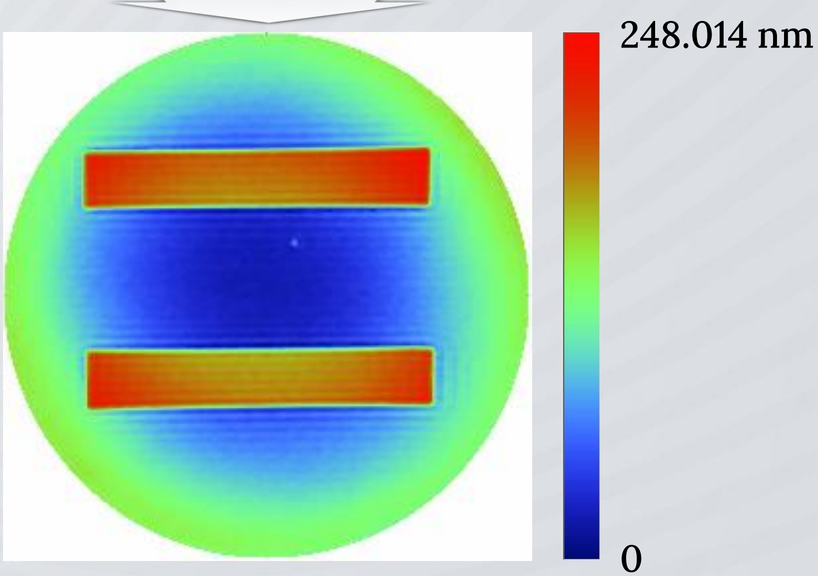
$$E_r = E r_0 \exp(i\theta)$$

$$E_1 = E r_1 t_0^{\,2} \exp\left[i(\theta+\varphi)\right]$$

$$E_2 = E r_2 t_0^{\,2} t_1^{\,2} \exp\left[i(\theta+\varphi-\Delta)\right]$$

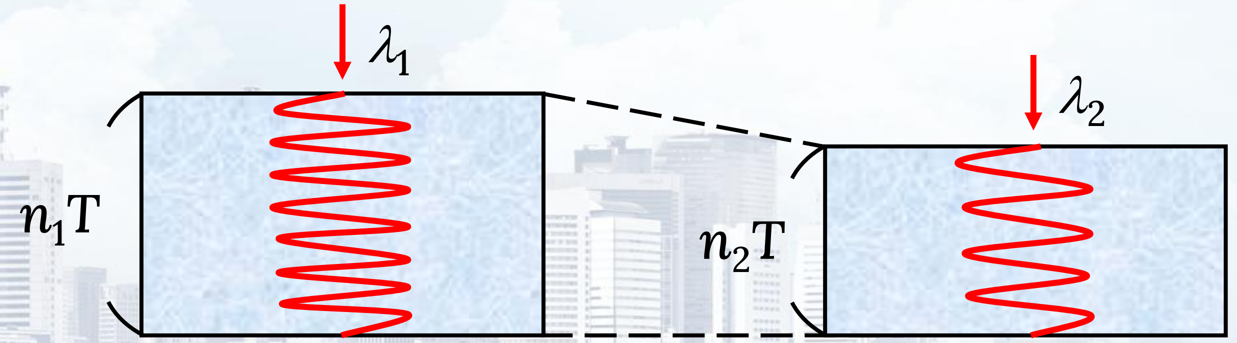
- Phase error ψ from phase difference Δ

$$\psi = \arctan \frac{B \sin \Delta}{A + B \cos \Delta}$$



Application 4 : Absolute Thickness Profiling

- Wavelength tuning from λ_1 to λ_2



$$n_1 T = \frac{\lambda_1}{2}(N_1 + p_1) \qquad n_2 T = \frac{\lambda_2}{2}(N_2 + p_2)$$

Absolute optical thickness at central wavelength λ_c [= $(\lambda_1 + \lambda_2)/2$]

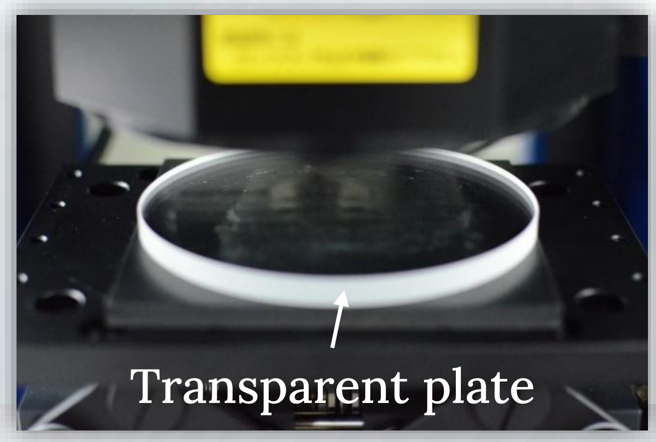
$$(n_g T)_{meas} = \frac{\lambda_s}{2}(N_1 - N_2 + p_1 - p_2)$$

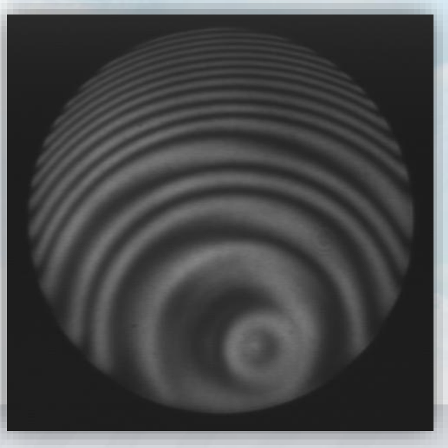
Group refractive index: $n_g = n\left(1 - \frac{\lambda}{n}\frac{dn}{d\lambda}\right)$

Synthetic wavelength: $\lambda_s = \frac{\lambda_1 \lambda_2}{\lambda_2 - \lambda_1}$

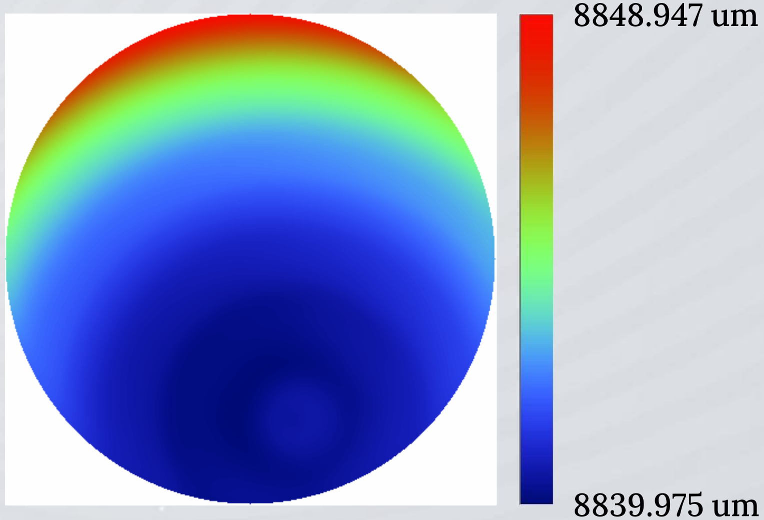
Number of intensity variation
: DFT analysis

Phase at initial and final wavelength
: fringe analysis using wavelength tuning
and 4N – 1 algorithm





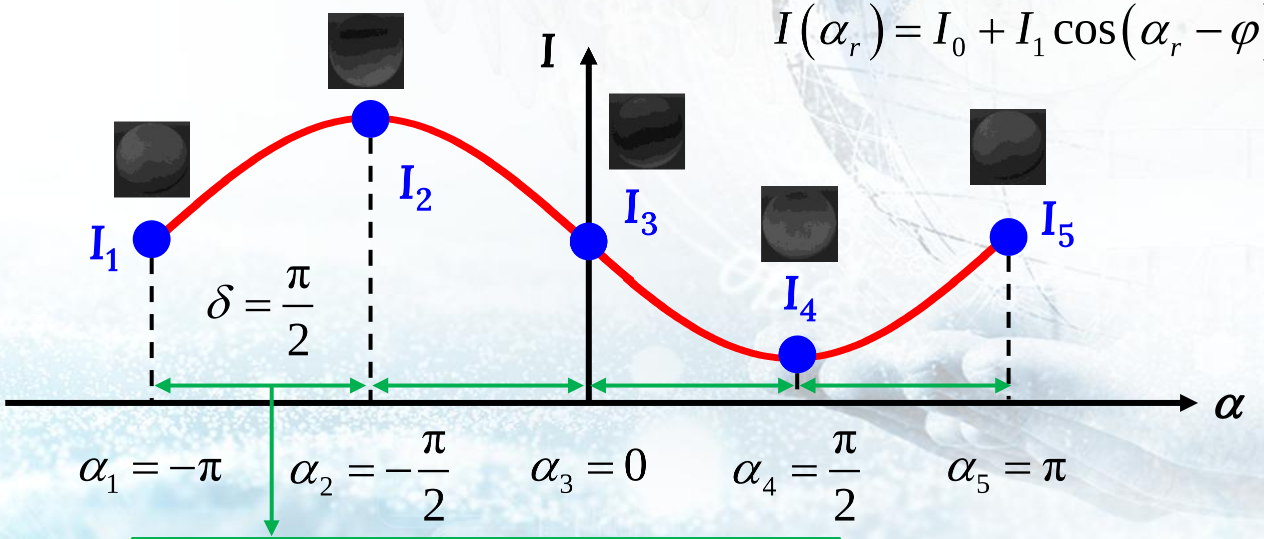
Final absolute optical thickness at λ_1



Background of Phase – Iterative Method

- Shortcomings of phase-shifting technique
  - Exactly same phase interval δ
  - Necessity of many frames for error compensation

$$I(\alpha_r) = I_0 + I_1 \cos(\alpha_r - \varphi)$$



Exactly same phase interval δ

Unrealistic!

- Simultaneous calculation of
  - Phase interval $\delta(\alpha_r)$
  - Target phase φ

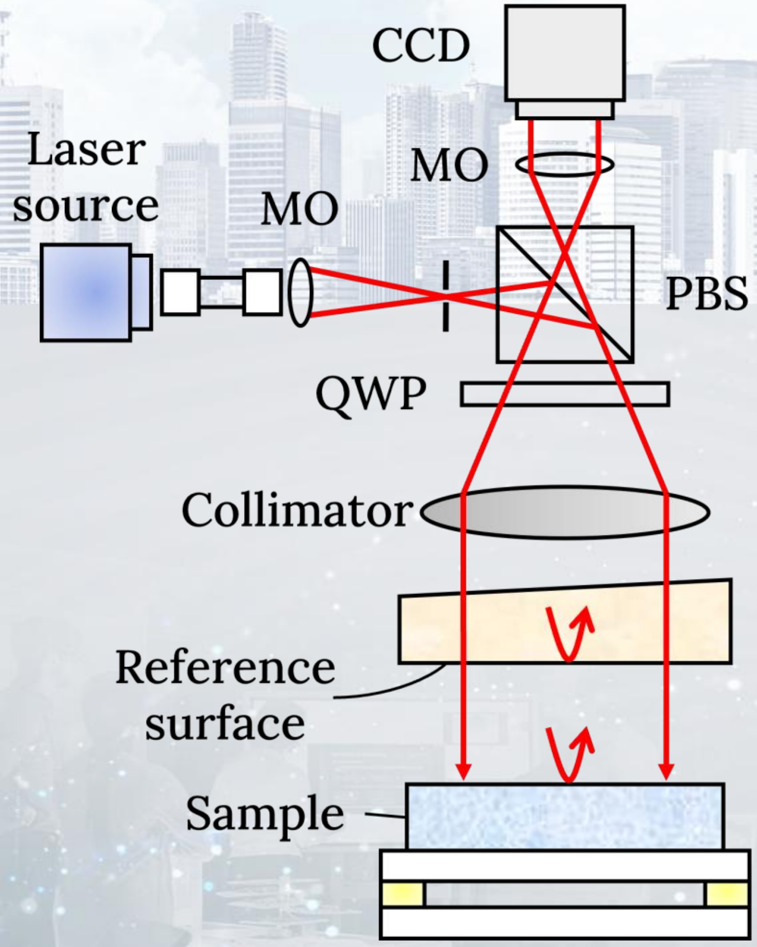
Phase-iterative method

Compensation ability for 2nd harmonics

Harmonic phase-iterative method

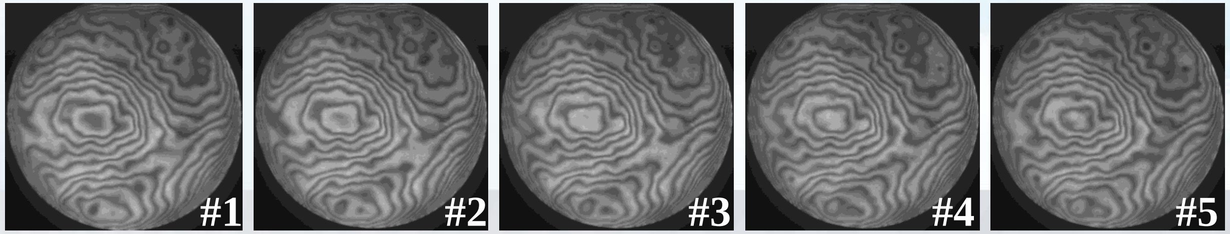
Application : Surface Topography of Wafer

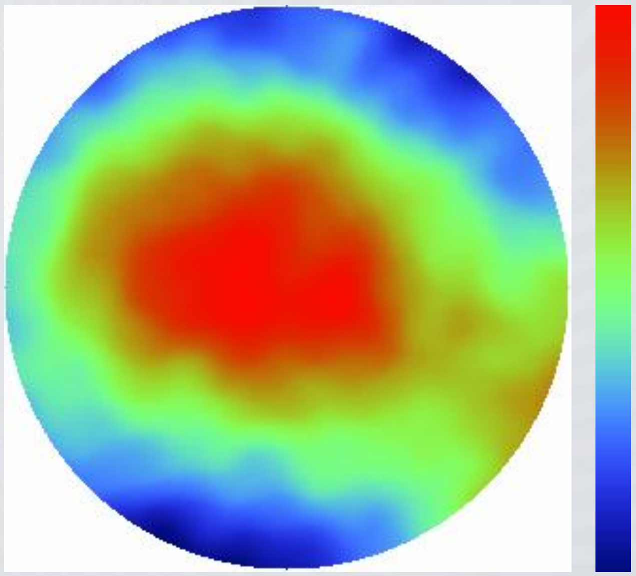
- **Larger-aperture Fizeau interferometer**



Reflectivity: 30%

- **Surface profiling of silicon wafer**
  - Surface of the four-inch silicon wafer was obtained by using the harmonic phase-iterative analysis and five-frame interferograms.

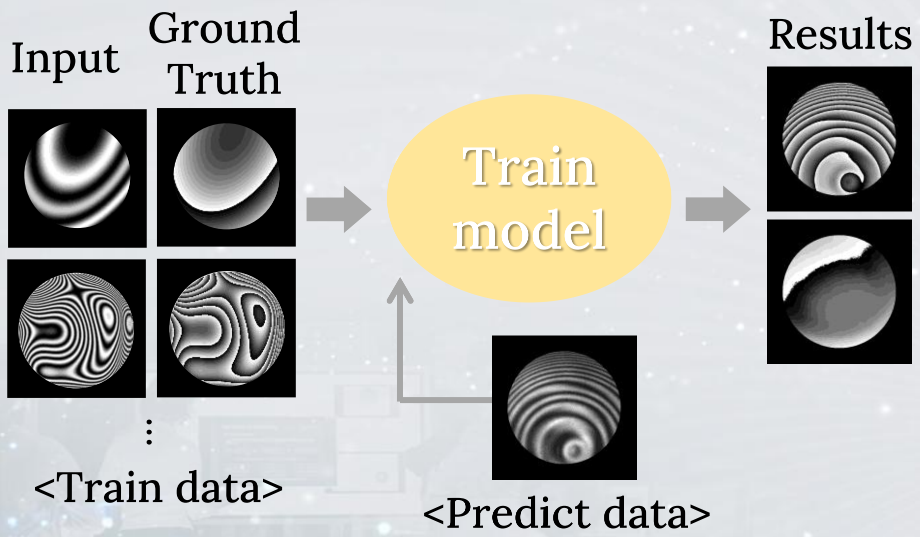




Repeatability uncertainty: 3.5 nm

Phase Extraction using Deep Learning

- Benefits of using deep learning
  - No systematic errors
  - Less than three interferograms
  - Fringe patterns with random phase shifts



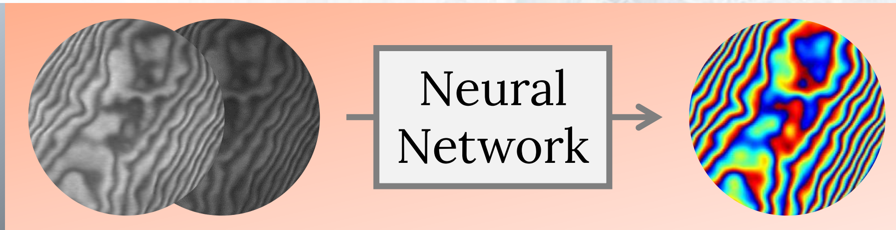
▶ Deep learning phase extraction

- Train data
  - One phase and fringe patterns are composed a train dataset
  - Simulation dataset (Not real data)
- Train model
  - Network, Layers, loss function, optimizer, and hyperparameters are determined
- Predict data
  - The predict data (real fringe patterns) is given to the trained model
- Results
  - The result phase corresponding to the predict data (interferograms) can be obtained.

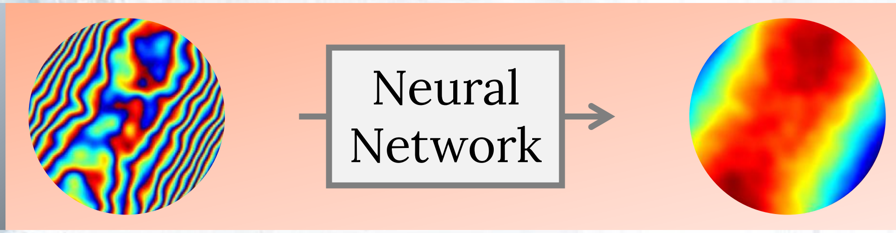
Fringe Analysis using Deep Learning

- On-going projects about fringe analysis using deep learning

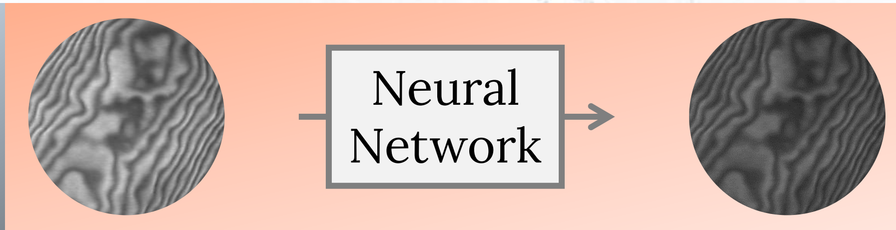
1 2-frame Phase extraction



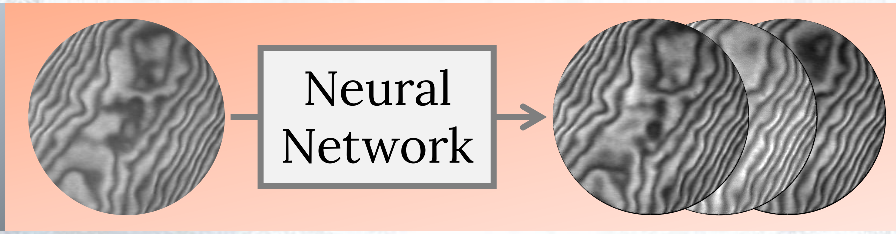
2 Phase unwrapping



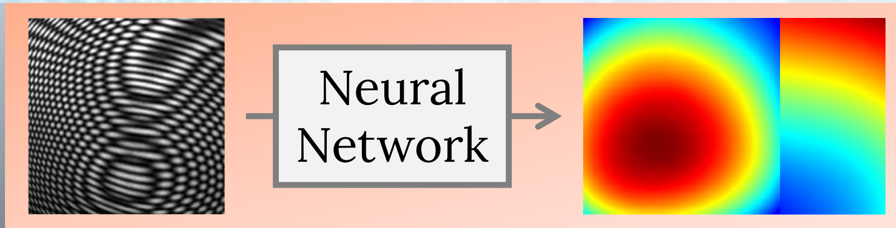
3 Fringe duplication



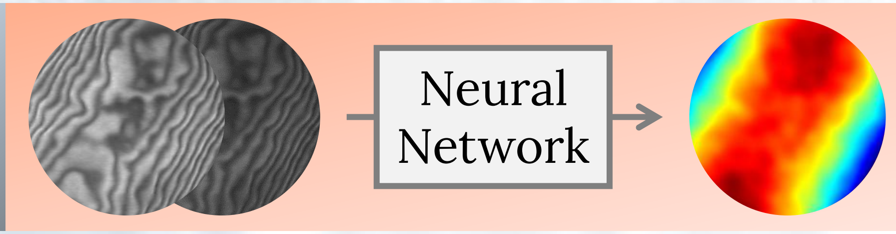
4 Fringe duplication for PST



5 Simultaneous profiling

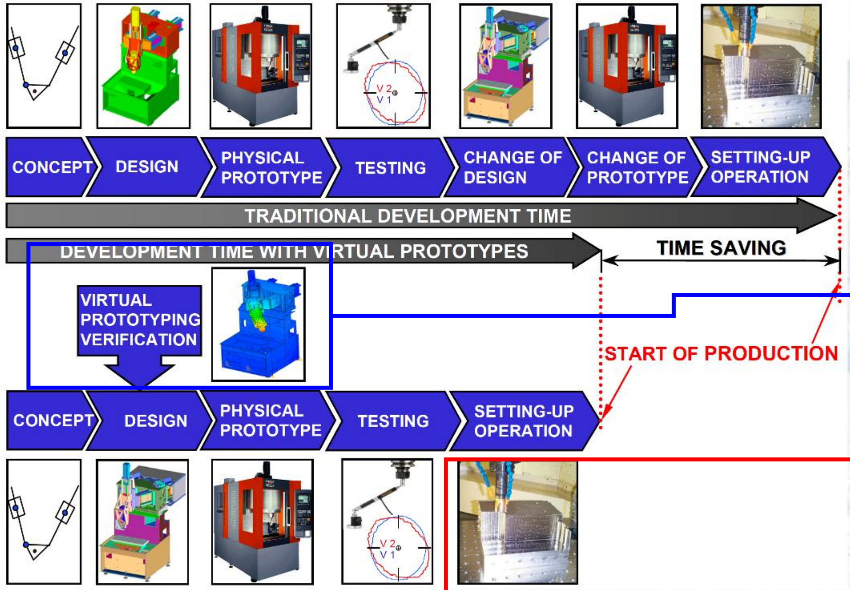


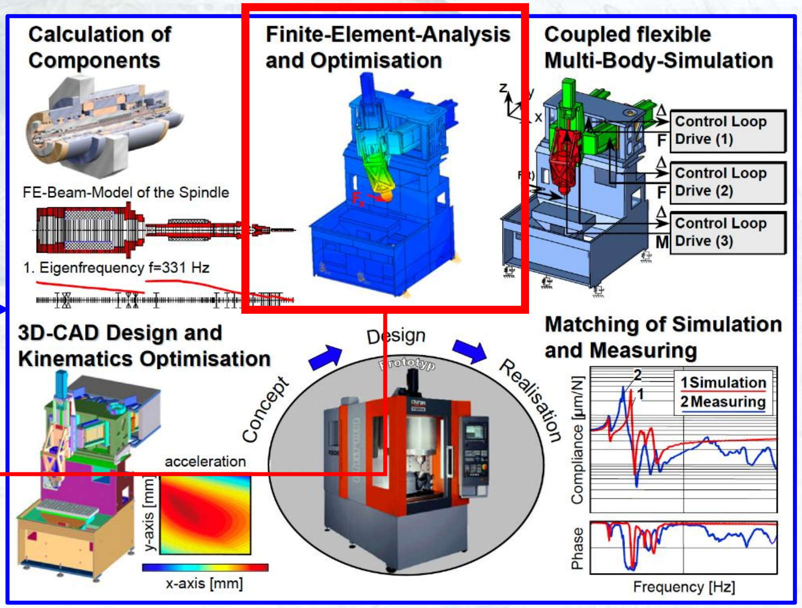
6 Absolute profiling

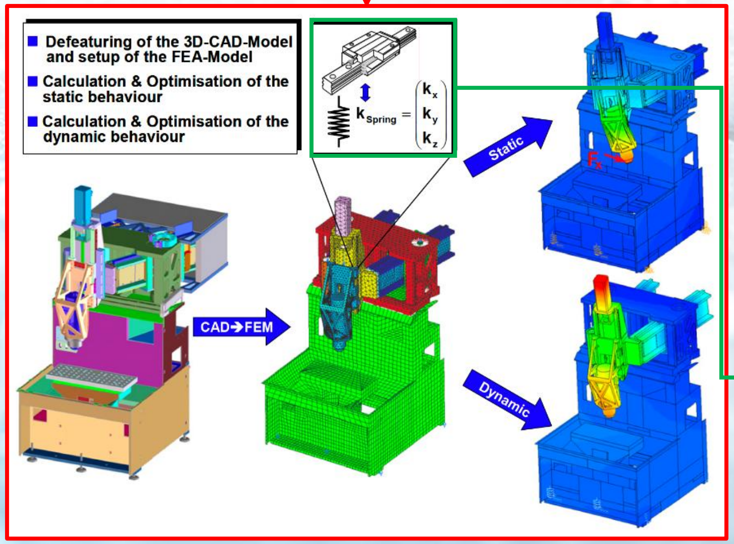


Machine Tools

Virtual Machine Tools







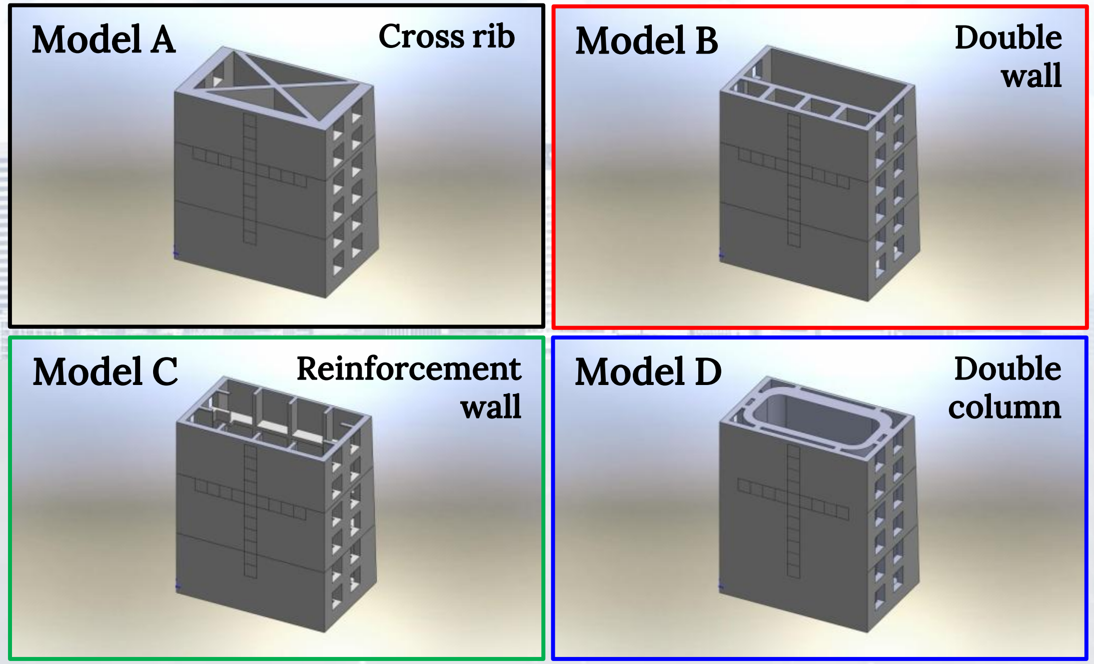
- Analysis types of FE analysis
  - Linear static
  - Nonlinear static
  - Dynamic
  - Thermal

Y. Altintas, C. Brecher, M. Weck, and S. Witt, “Virtual machine tool,” CIRP Annals **54**(2), 115–138 (2005).

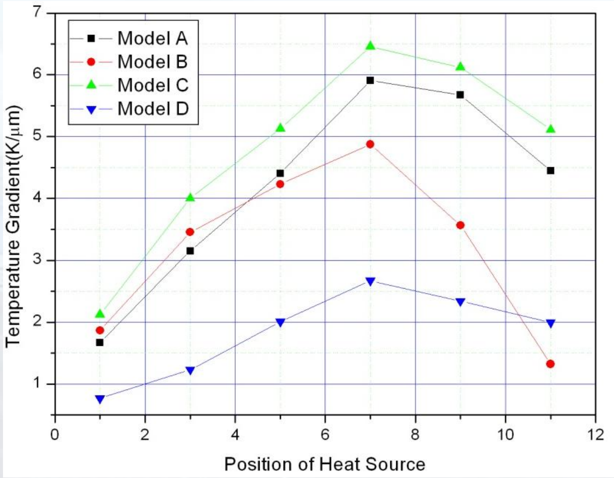
Modeling of machine tool joints

Thermal Properties of Column by Rib Structure

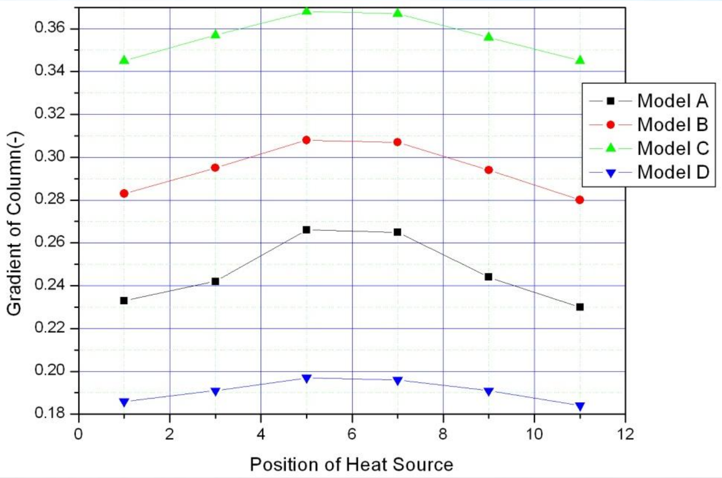
- Column rib model



- Temperature gradient



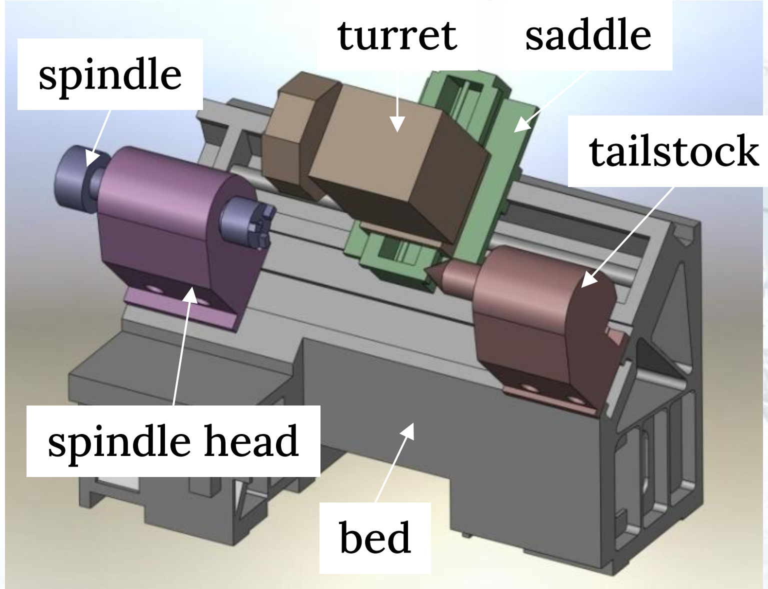
- Deflection gradient



- Model D (double column model) shows the best thermal performance from the aspect of temperature gradient and deflection of column
- Model C (reinforcement wall model) does not have the good thermal properties because the deflection of column is too large

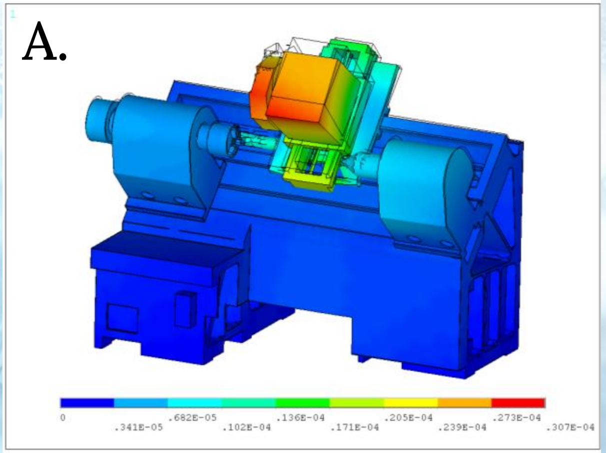
Structural Analysis of Turning Center

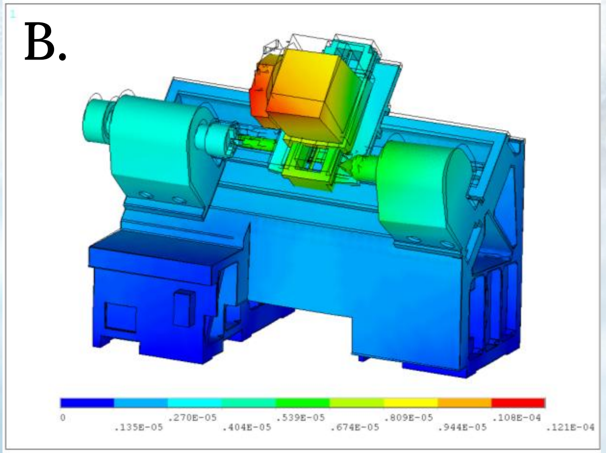
- Suppression of static deflection of turret of hard tuning center using CFRP



	Density [kg/m³]	Young's modulus [GPa]	Poisson ratio
GC300	7,300	90.0	0.25
USN150	1,550	E_1 = 130.0, E_2 = 10.0, G_{12} = 5.06	0.28

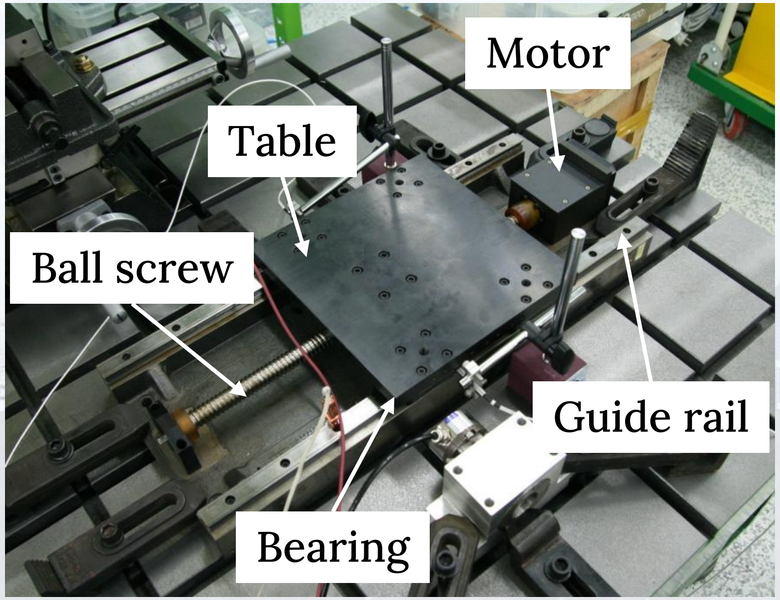
A. GC300
B. turret (USN150), others (GC300)



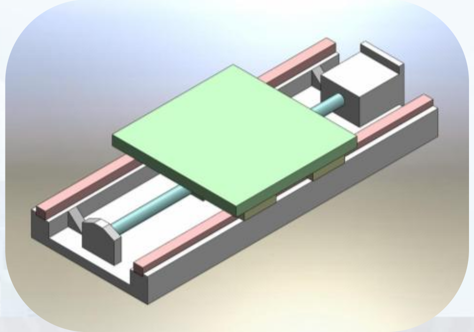


A. Max. deflection
: 30.7 um
B. Max. deflection
: 12.1 um

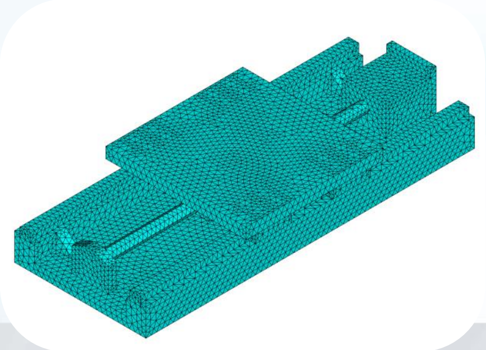
Modeling of Machine Tool Joint – Feed Drive



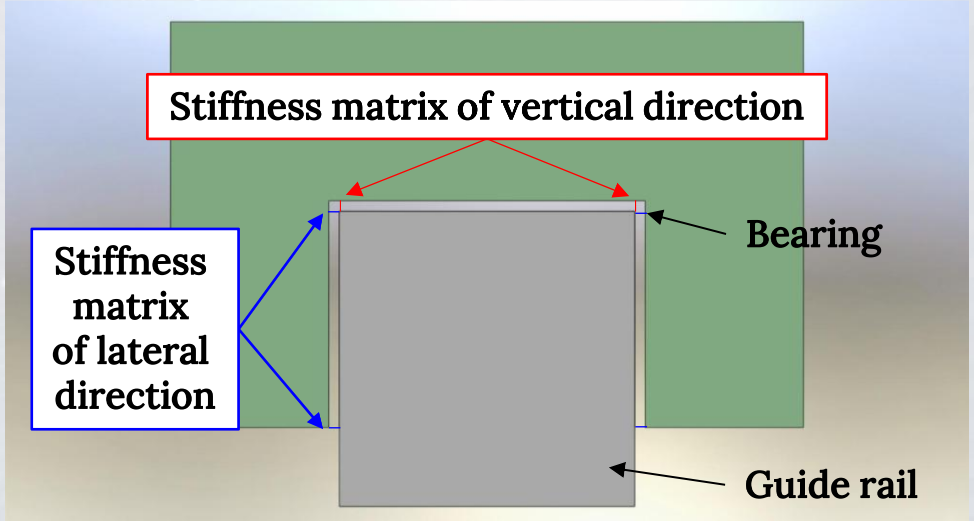
- 3D CAD modeling



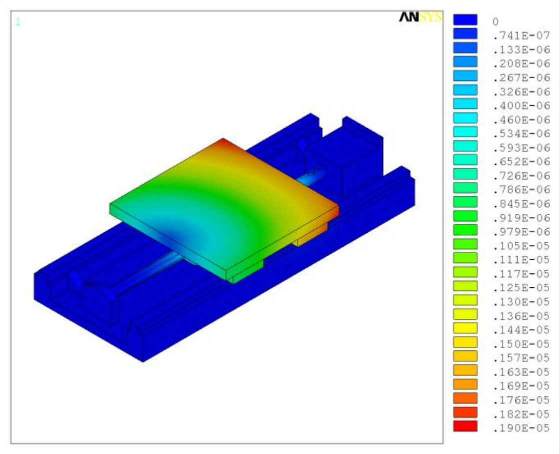
- FEA modeling



- Stiffness matrix



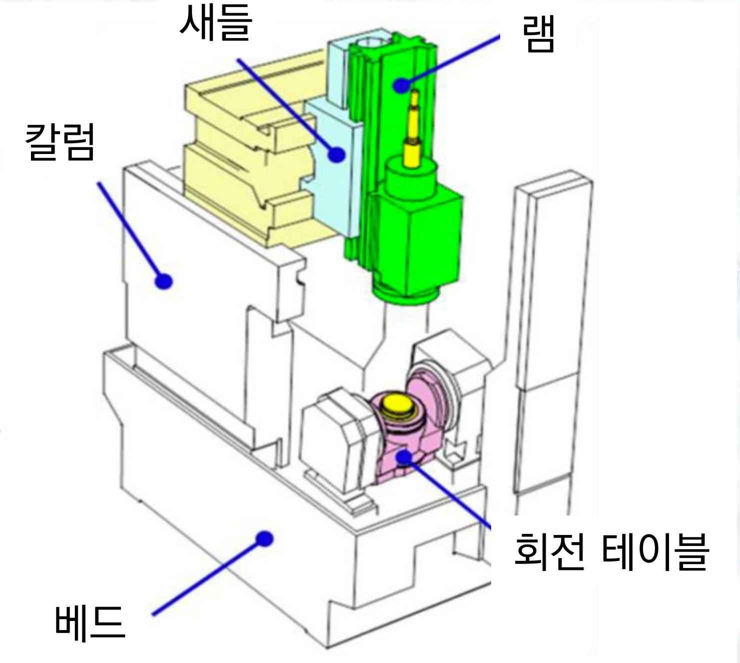
- FEA analysis



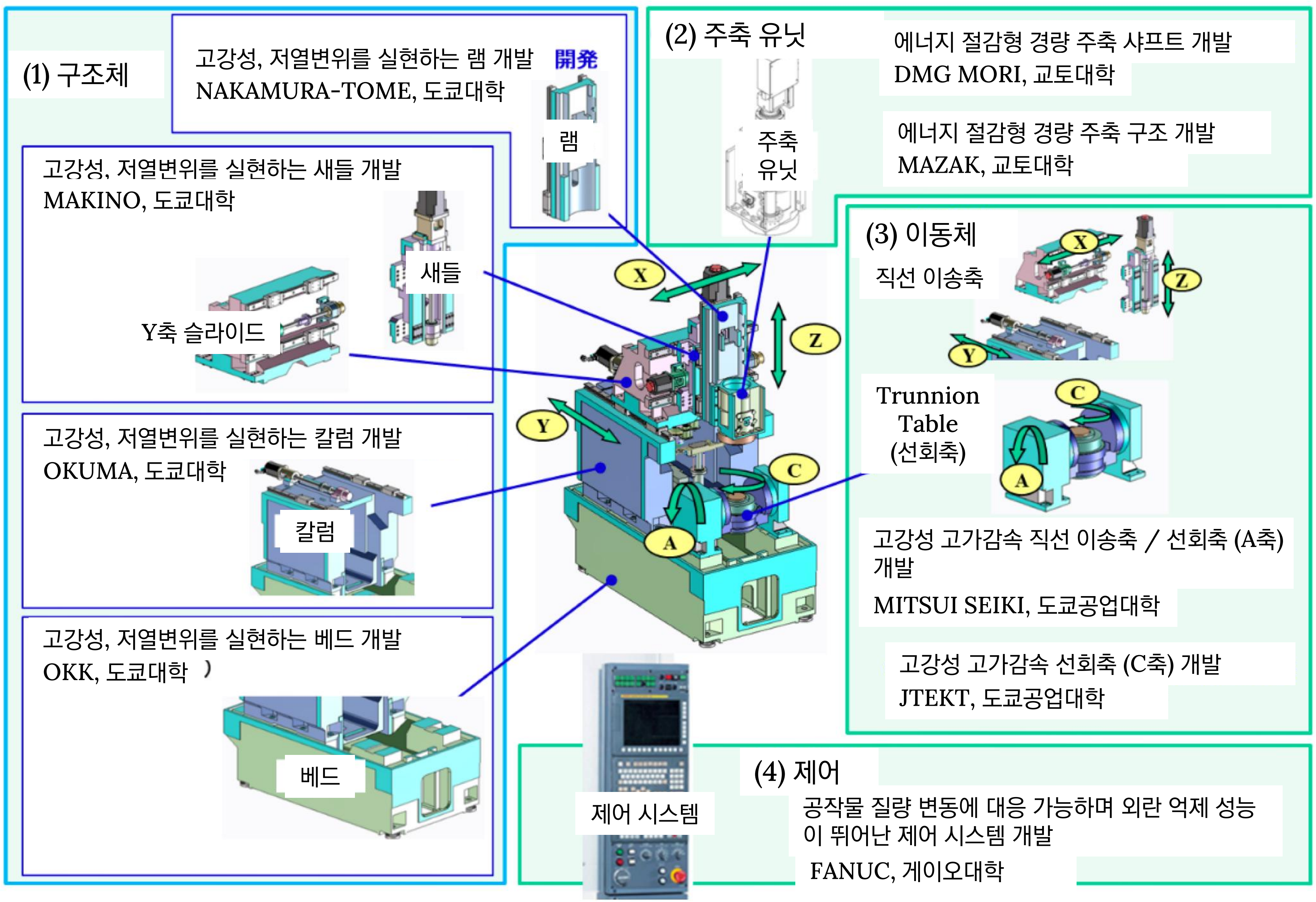
CFRP Machine Tools

- 기술개발책임자: A. Ieki (OKUMA)
- 대표실행책임자: H. Senda (OKUMA), N. Sugita (The University of Tokyo)

구조체 (칼럼, 베드, 새들, 램)	MAKINO, OKUMA, OKK, Nakamura-Tome	東京大学 THE UNIVERSITY OF TOKYO
주축 및 주축 구동부	DMG MORI, Mazak	京都大学 KYOTO UNIVERSITY
직선 이송 시스템 및 회전 테이블	MITSUI SEIKI, JTEKT	東京工業大学 Tokyo Institute of Technology
제어 시스템	FANUC	慶應義塾 Keio University



CFRP Machine Tools



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CFRP Machine Tools

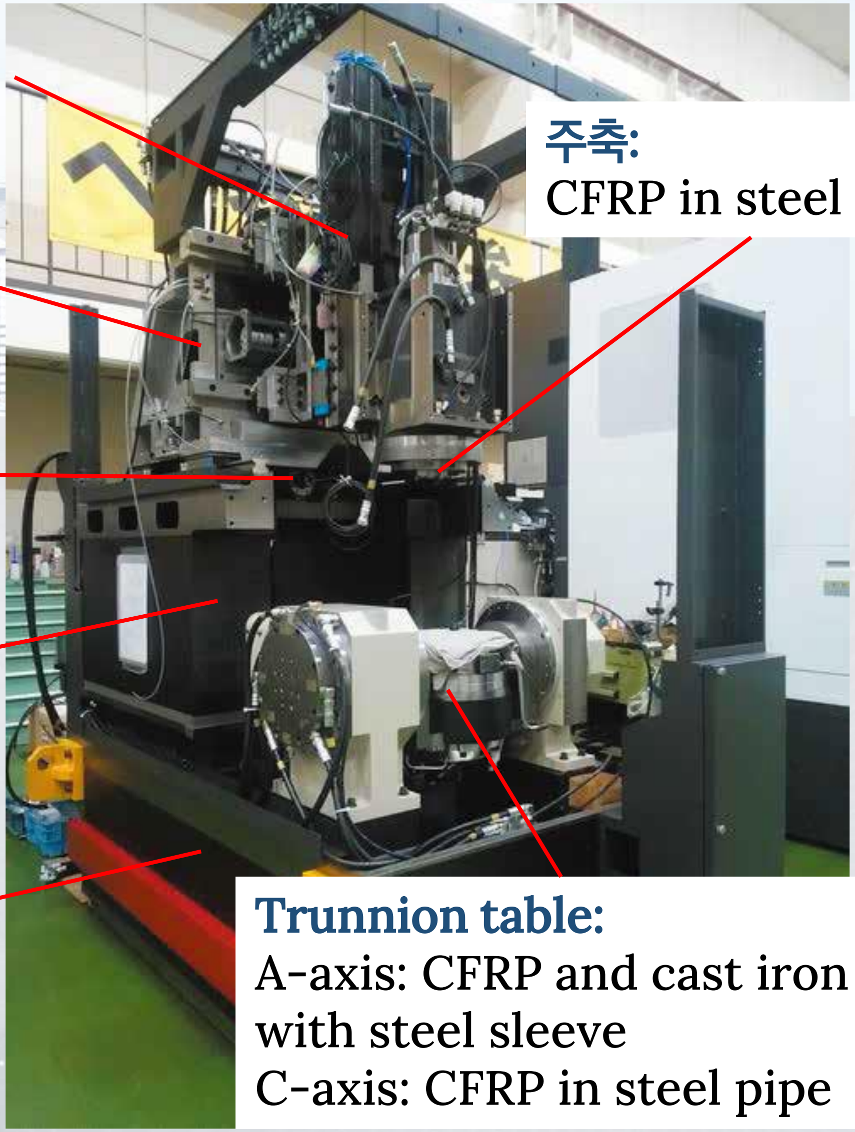
램:
CFRP in steel square pipe

새들:
CFRP + Aluminum alloy

이송축:
CFRP in steel pipe

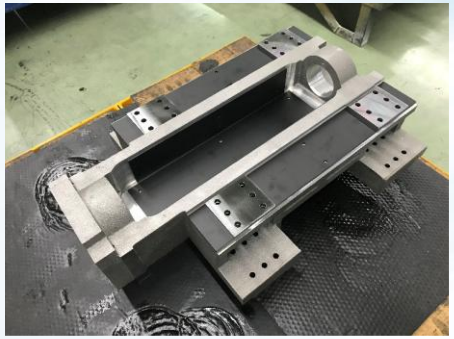
칼럼:
CFRP & REC in gray cast iron

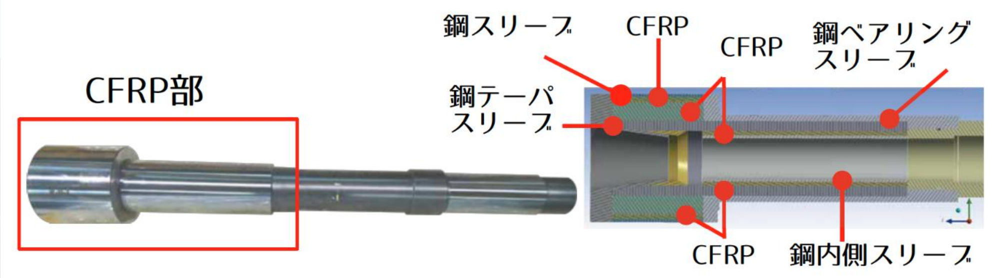
베드:
CFRP & REC in gray cast iron

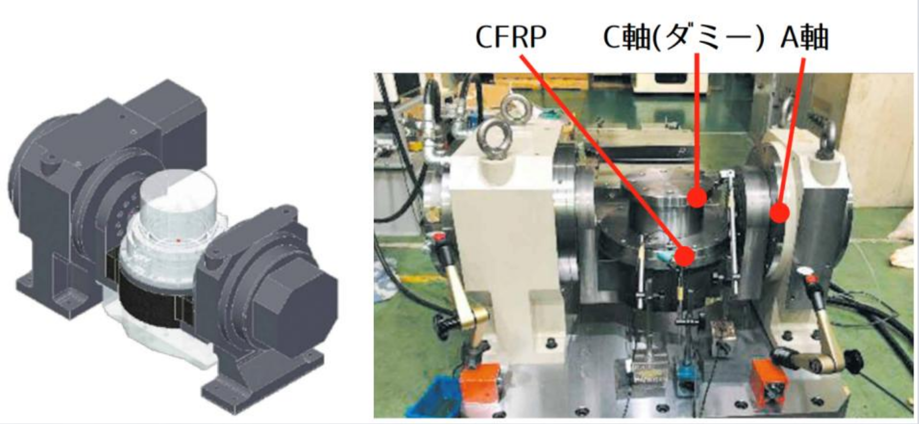


주축:
CFRP in steel pipe

Trunnion table:
A-axis: CFRP and cast iron with steel sleeve
C-axis: CFRP in steel pipe





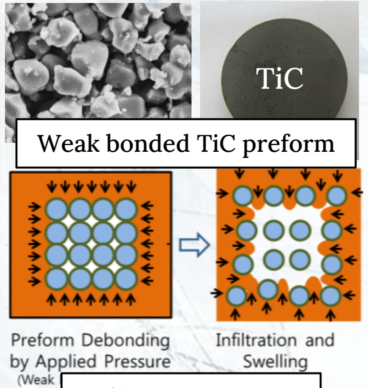


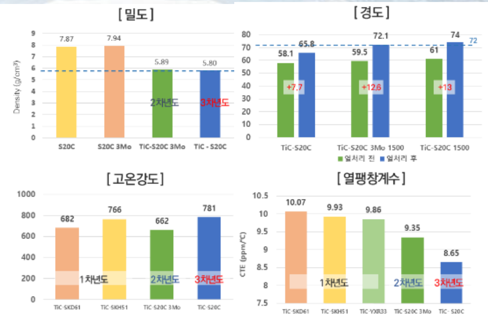
Development of Steel Composite

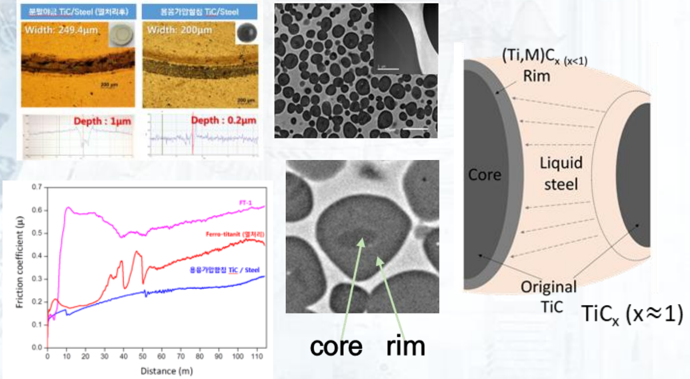
- 비철기지 금속복합소재 제조에 사용하던 용융가압함침공정의 개념을 응용하여 철강기지 금속복합소재 개발을 시도하여 이 분야 새로운 장을 개척 (용해온도 1,000 ℃ → 1600 ℃)

  - 용융가압함침공정 개념설계/장치제작/최적제조공정/특성제어 등

- 온도: ~2000 ℃
- 가스압: 최대 30 atm
- Two chamber system
- 최대 Φ250 시제 제조







[독자기술 용융가압함침 공정 장비]

[우수한 물성: 경량, 고강도, 저열팽창, 고내마모]

<응용 연구를 통하여 확보한 기술>

- TiC_p/Steel(금형강(SKD61), 공구강(SKH51), 저탄소강(S20C), 스테인레스강(SUS431))
- 강화재 형상 및 강화재 체적율 제어
- 계면구조(TEM) 및 미세조직 형성기구 규명 (Ostwald ripening (core-rim 구조))
- 조성/계면/분산 제어를 통한 우수한 물성 확보 및 신뢰성 향상(데이터베이스)
- 대형시제 제조 (Φ200, 35t / 200 mm 급) 및 응용분야 맞춤 물성 제어
- 응용물성 해석: 스핀들 적용시 우수한 열적(저열변형)/동적(진동) 특성

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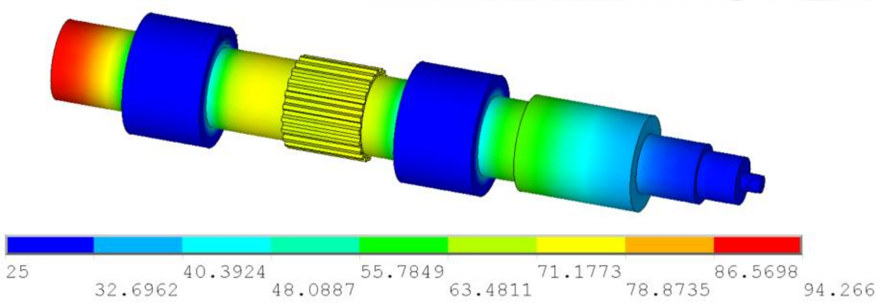
KIMS 한국재료연구원

Thermal Analysis of Steel Composite Spindle

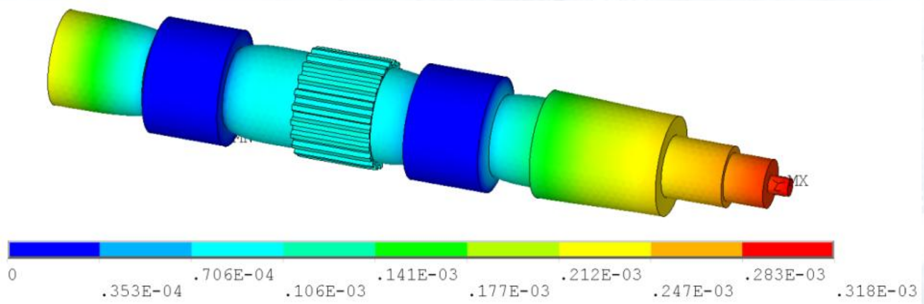
	Specific heat [J/kg·K]	Density [g/cm³]	Young's modulus [GPa]	Poisson ratio	Thermal conductivity [W/m·K]	Coefficient of thermal expansion [10^{-6}/K]
TiC-SUS431 (KIMS)	551	6.12	240	0.28	15.1	8.74
SUS431	480	7.76	200	0.30	21.3	10.09
GC300	565	7.30	90	0.25	55.8	17.10

- Temperature distribution



	Maximum Temperature [°C]
TiC-SUS431	94.2
SUS431	102.9
GC300	104.1

- Thermal deflection



	Thermal deflection [um]
TiC-SUS431	318
SUS431	379
GC300	848

KEIT Project (산업통상자원부 소재부품개발사업)

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- 과제명 : 가공 성능 최적화 및 사용편의성 향상을 위한 스마트 공작기계용 지능화 요소 기술 개발
  부산대 과제명: 민감도 분석법과 보정 알고리즘을 이용한 5축 공작기계 Kinematic Error 보정 시스템 개발

- 연구개발 목표
  - ❖ 차세대 다축 복합 스마트 머신의 가공 정밀도와 생산성을 향상시킬 수 있는 지능화 요소기술 개발
  - ❖ 개발된 요소기술의 개방형 운영체제 탑재 및 실증

- 수행기간 : 2023. 07. 01 ~ 2026. 12. 31. 총 42개월

- 연구 컨소시엄 구성
  - ❖ 주관기관 : 한국기계연구원 (책임자 : 노승국 책임연구원)
  - ❖ 공동연구개발기관 : ㈜DN솔루션즈 (책임자 : 이창호 책임매니저)
  - ❖ 공동연구개발기관 : 연세대학교 산학협력단 (책임자 : 윤준영 교수)
  - ❖ 공동연구개발기관 : 부산대학교 산학협력단 (책임자 : 김양진 교수)
  - ❖ 공동연구개발기관 : 경희대학교 산학협력단 (책임자 : 엄주명 교수)

KEIT Project (산업통상자원부 소재부품개발사업)

AMOI
Advanced Manufacturing & Optical Instrumentation Lab

- Smart Machine 의 핵심 지능화 기술:
  AI, IoT, DX등의 최신 기술을 융합하여 장비의 상태를 스스로 인지/판단하여 높은 생산성과 효율성 실현

C 보정 (Compensation)

- 절삭부하 감지 기능
- 열변위 보정 기술
- 5축 기하오차 측정/보정 기능
- 밀턴 테이블 불평형 검출 기술
- 능동형 진동 저감 기술

DN SOLUTIONS
연세대학교 YONSEI UNIVERSITY
부산대학교 PUSAN NATIONAL UNIVERSITY

다축 복합 스마트 가공기

P 예측/알림 (Predictive/alerts)

- 비전 센서 기반 공구 파손 검출 기능
- 부품 교체 주기 자동 알림 기능 (DN SOLUTIONS)
- 장비 상태 모니터링/예지보전 기술
- 충돌방지기술 (KIMM 한국기계연구원 KOREA INSTITUTE OF MACHINERY & MATERIALS)
- 스핀들 상태 진단 기술

O 최적화 (Optimization)

KIMM 한국기계연구원 KOREA INSTITUTE OF MACHINERY & MATERIALS

- 비접촉식 조도측정기를 통한 가공조도 및 품위 측정 기술
- 가공 조건 최적화 기술 (오프라인)
- 자동 공정 스케줄링 기능
- 생산성 향상을 위한 프로그래밍 최적화 기술
- Smart CBS 기능 (DN SOLUTIONS)

U UX (User-eXperience)

KIMM 한국기계연구원 KOREA INSTITUTE OF MACHINERY & MATERIALS
경희대학교 KYUNG HEE UNIVERSITY

- 자동 공구 정보 인식 기능 (Tool-ID)
- 가공조건 실시간 편집 및 저장 기능
- 실시간 칩 처리 기능 / 대화형 장비 (운전/유지보수)
- NC 중립 HMI H/W & S/W 플랫폼
- 음성 인식 기술 / 모바일 원격 제어 기능
- 긴급 호출 기능 / 자동 전원 및 워밍업 제어 기능

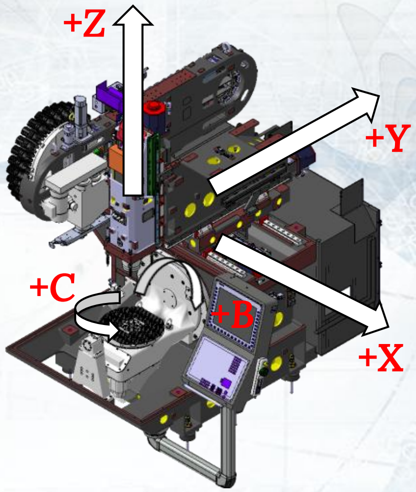
(빨간 점선 박스) 본과제 개발 영역 – 우선순위 및 개발 일정 고려하여 선정

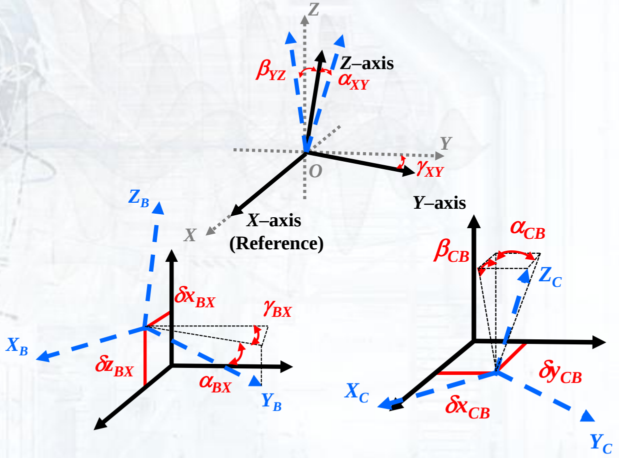
5축 공작기계 오차 보정

- 5-Axis machine tool

DVF 5000 (DN Solutions)

- Kinematic error modeling



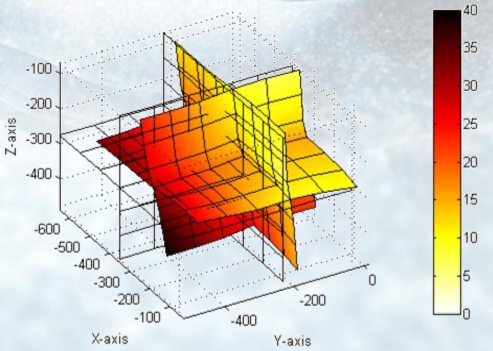


Kinematic error

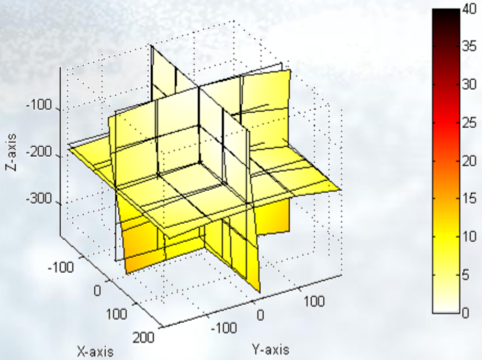
- Identification of kinematic error

Measurement cycle

- Compensation of volumetric error



Before compensation



After compensation

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Advanced Manufacturing & Optical Instrumentation Lab.

첨단생산 및 광계측 실험실

Pusan National University

School of Mechanical Engineering

Prof. Yangjin Kim

Lab Alumni (Mar. 2025)

AMOI
Advanced Manufacturing & Optical Instrumentation Lab

Miss Jiwon Seo

FEB 2022
SK on

Dr. Wonjun Bae

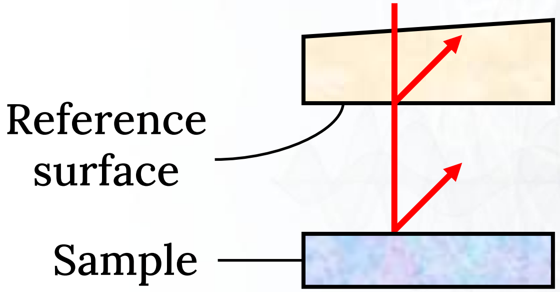
FEB 2023
DN Solutions

Dr. Sungtae Kim

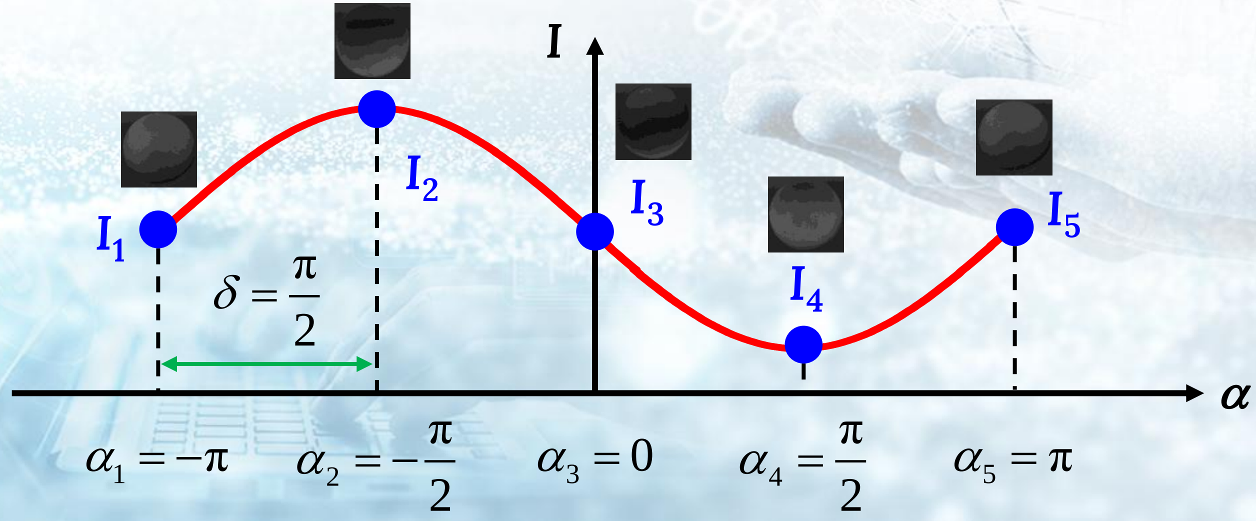
FEB 2024
DN Solutions

Conventional Phase – Shifting Technique

- Simple two-layer Fizeau interferometer



- During wavelength tuning $I(\alpha_r) = I_0 + I_1 \cos(\alpha_r - \varphi)$



- Phase-shifting algorithm

$$\varphi = \arctan \frac{\sum_{r=1}^{M} b_r I(\alpha_r)}{\sum_{r=1}^{M} a_r I(\alpha_r)}$$

r: sampling number

a_r, b_r: sampling amplitudes

M: image number for phase calculation

- Error sources
  - ✓ Harmonic components
  - ✓ Phase-shift error
  - ✓ Coupling error (between harmonics and phase-shift error)
  - ✓ Nonlinear error (vibration, temperature fluctuation)

Design Methods of Phase – Shifting Algorithm

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- **Linear equation theory** (proposed by K. Hibino)
  - Group of linear equations for the elimination of phase-shift errors
  - 9-frame, 13-frame, etc.
- **Characteristic polynomial theory** (proposed by Y. Surrel)
  - Flexible design method using polynomial of algorithm
  - Applicable to simultaneous measurement of surface shape and thickness
  - 17-frame, 13-frame, 19-frame, 15-frame, etc.
  - 3N – 2, 4N – 3, 5N – 4, 6N – 5, 7N – 6, etc.
  - 4N – 1, 5N – 2, 6N – 3, etc.
- **Extended averaging method** (proposed by K. Creath)
- **Fourier description method** (proposed by K. Freischlad and C. L. Koliopoulos) • • • •

$$\varphi = \arctan \frac{\sum_{r=1}^{M} b_r I(\alpha_r)}{\sum_{r=1}^{M} a_r I(\alpha_r)}$$

a_r, b_r: sampling amplitudes

M: image number