Multi-Channel Random-Quadrature Receiver for Industrial Laser-Ultrasonics

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Multi-Channel Random-Quadrature (MCRQ) Interferometer

- Principle of operation
- Optical design
  - Fiber design (Free-space design)
- Electronic demodulation
  - Rectified
  - Linear
- Characterization & results
- Conclusions
Multi-Channel Random-Quadrature (MCRQ) Interferometer

**Principle**
- Classic reference beam interferometer architecture
- Use of a detector array instead of single-element detector
- Parallel processing for each channel

![Diagram of MCRQ Interferometer](image)

**Single detector interference signal**

\[ 2 \sqrt{I_{\text{Ref}} \cdot I_{\text{Obj}} \cdot \cos(\phi_{\text{LF}}(t) + \phi_{\text{UT}}(t))} \]

- \( \phi_{\text{LF}} \): Speckle Phase  /  \( \phi_{\text{UT}} \): Ultrasonic Phase  /  \( I_{\text{Ref}} \) & \( I_{\text{Obj}} \): Reference Beam and Object Beam Intensities
Compact Fiber Design

Partial reflection (~5%) at the fiber end generating the reference beam.

Multi-channel Detector - 1

Multi-channel Detector - 2

PBS: Polarizing Beam Splitter

Optical Isolator

Laser

Signal Processing

Complete system with internal 1-Watt laser

Optical Head

MULTIMODE FIBER (50μm)

PARTIAL REFLECTION Not used (AR coating)

Fiber tip mounted on vibrating piezo

PARTIAL REFLECTION (~5%) AT THE FIBER END GENERATING THE REFERENCE BEAM

光学头
Salient Features of Fiber Design

- **Multimode fiber**
  - Same fiber for delivery and collection
  - Not critical coupling/alignment

- **Fiber length is not critical**: *Path difference between interfering beams is independent of fiber length*

- **Faraday isolator**
  - Protect laser from feedback
  - Efficient use of collected light
  - No polarization losses

- **For optimal detection**
  - Dominant noise source → Shot noise from reference beam
  - Higher frequency requires higher intensity on detector (*laser power / reflection coefficient at fiber end*).
  - Electronic noise 5dB below total noise → 17% added noise compared to shot-noise limit.
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- Laser Power = 500mW / \( \lambda = 532 \text{nm} \)
- Reflection at uncoated fiber end ~ 4.5%
- Detector Array: 2 x 25-Element
- Detection bandwidth = 50MHz
Electronic Demodulation

- **Single detector interference signal**
  \[ 2 \sqrt{I_{Ref} \cdot I_{Obj}} \cdot \cos(\phi_{LF}(t) + \varphi_{UT}(t)) \]

- **Homodyne interferometer transfer function**

- **Uniform speckle phase distribution**: 50% In-quadrature + 50% Out-of-quadrature
  \[ (\phi_{LF} = -\pi/2, +\pi/2) \] \[ (\phi_{LF} = 0, \pi) \]

- **Demodulation**
  To remove the sign ambiguity: Correction needed for each channel
Absolute Amplitude Demodulation

**Single detector signal (AC only)**

\[
\cos(\phi_{LF}(t) + \varphi_{UT}(t)) \rightarrow \cos(\phi_{LF}(t)) \cdot \cos(\varphi_{UT}(t)) - \sin(\phi_{LF}(t)) \cdot \sin(\varphi_{UT}(t)) \approx 1
\]

- Low frequency
- High frequency, small amplitude

After high-pass filter (Background vibration rejection)

\[
\cos(\phi_{LF}(t)) - \sin(\phi_{LF}(t)) \cdot \varphi_{UT}(t)
\]

**Rectification and multi-channel summation**

\[
\sum_{n} |\sin(\phi_{LF}(t))| \cdot |\varphi_{UT}(t)| = |\varphi_{UT}(t)| \sum_{n} |\sin(\phi_{LF}(t))| \rightarrow n \cdot \frac{2}{\pi}
\]

- Simple electronic design
- Low-cost
- Off-the-shelf components
- Output \( \propto \) Rectified displacement
- Stability increases with the number of channels
Demodulation overview

- **Demodulation based on signal rectification.**
  - Simple and robust setup
  - Very effective rejection of background noise vibration (electronic filtering)
  - Direction of displacement is not known

- **Linear demodulation**
  - To use the same compact multi-channel architecture with simple demodulation scheme in order to get an output signal proportional to the displacement.
  - Principle:
    - To introduce a known perturbation
    - Direction of displacement is known by monitoring the known perturbation
    - Sign correction applied for each channel before summation
Linear Demodulation — Principle —

- To introduce a known perturbation
  - Doppler shift
  - Small single frequency vibration
Linear Demodulation — Principle —

- To introduce a known perturbation: \( \cos(\phi_{LF}(t) + \text{perturbation} + \varphi_{UT}(t)) \)

  - Doppler shift
  - Small single frequency vibration

  High-Frequency component of the interference signal
  \[ V_{HF} \propto -\sin[\phi_{LF}(t)] \cdot \varphi_{UT}(t) + \varphi_{LF}(t) + \varphi_{UT}(t) \sin(\omega_{R} \cdot t) \]

  Sign Ambiguity

  Speckle & LF vibration

  UT Signal

  Small Reference Signal @ \( \omega_{R} \)

  Amplitude of Interference signal at \( \omega_{R} \)
  \[ V_{\omega_{R}} \propto -\sin[\phi_{LF}(t)] \cdot \varphi_{R} \]

  Monitoring the phase of the interference signal at \( \omega_{R} \)
  \( \Rightarrow \) Lock-in detection

  Monitoring the sign to remove ambiguity

  Requirement: \( \omega_{D} > \frac{\partial \phi_{LF}(t)}{\partial t} \) (Doppler perturbation dominates)

  Low-Frequency component of the interference signal
  \[ V_{LF} \propto \cos[\phi_{LF}(t) + \omega_{D}t] \]

  Derivative of Low-Frequency component
  \[ \frac{\partial V_{LF}}{\partial t} \propto -\sin[\phi_{LF}(t) + \omega_{D}t] \left( \frac{\partial \phi_{LF}(t)}{\partial t} + \omega_{D} \right) \]
Linear Demodulation – **Principle** –

- **To introduce a known perturbation**
  - Doppler shift
  - Small single frequency vibration

- **For each channel:**
  - Monitoring of the perturbation
  - To put each channel in-phase

- **Doppler shift detection**
  - LF signal
  - Comparator
  - Logic control

- **Lock-in detection** (Small single frequency vibration)
  - HF signal
  - XOR
  - Comparator
  - Logic control

- **System Diagram**
  - HF signal
  - Polarity Select
  - Switch
  - Polarity Detector
  - Control
  - R
  - C
  - Derivator
  - Comparator
  - Logic control

**Diagram Elements:**
- **Polarity Detector**
- **Control**
- **Switch**
- **LF signal**
- **Comparator**
- **Logic control**
- **R**
- **C**
- **Derivator**
- **XOR**
- **Calibration Reference**
- **Time**

**Footer:**
June 2013 – LU2013
Linear Demodulation — Principle —

- To introduce a known perturbation
  - Doppler shift
  - Small single frequency vibration

- For each channel:
  - Monitoring of the perturbation
  - To put each channel in-phase

- Summation of in-phase channels
Linear Demodulation — Schematic —
(With Lock-in on small single frequency vibration)
Linear Demodulation – Performances –

- Laser Power = 500mW / $\lambda$=532nm
- Detector Array: 2 x 25 elements
- Calibration signal @ 1MHz
- Detection bandwidth = 50MHz

**Frequency response** (Detection Bandwidth=50MHz)

- 1MHz Calibration
- Output Noise
- Electronic noise
- 50MHz

**Rejection of Intensity noise**

*After differential amplifier:*
- Intensity noise (coherent) is subtracted
- Shot noise (random) is added
System Performances & Features

• Detection bandwidth (for electronic noise < shot noise)
  • 50MHz → 500mW laser power
  • Higher bandwidth → higher laser power

• Adaptation time
  • Linear Demodulation (lock-in + switch response) → ≤ 15μS
    → Switching occurs when channel is not sensitive
  • Rectified Demodulation → set by high-pass filter → ≤ 2μS (F_c=1MHz)

• Reference signal → Can be set below or above the detect bandwidth

• For on-line application → linear demodulation using the Doppler induced by off-normal observation of moving target
Linear vs Rectified
- side-by-side comparison -

PIEZo (Ø1/2 inch) (2.25MHz)

SAMPLE - Rough surface - (Aluminum, 12.5mm thick)

Experimental Setup
Interferometer (rectified demodulation)
Interferometer (linear demodulation)

Piezo

Oscilloscope Display
- Single Shot signals -

- Detection Bandwidth [20MHz] -
Monitoring of ultrasonic emission (UE) during Laser welding*

**APPLICATION:** In-process monitoring of weld quality by continuous monitoring of the ultrasonic emission (UE) generated by the welding process during high-speed laser welding.

**EXPERIMENTAL SET-UP:**
- Welding system: 600W CW Laser
- Samples: 100μm thick stainless steel
- Detection BW: [200kHz – 10MHz]
- Welding speed = 100mm/s
- Offset (weld - detection)= 5mm
- UE integration window = 200μs

* Collaboration with the Edison Welding Institute, Dayton, OH.
Thickness measurement on moving sample

Sample:
- Oxidized steel plate, 2mm thick
- Rotating sample, Transverse velocity up to 3m/s

Detection:
- MCRQ interferometer ($\lambda=532\text{nm} / 200\text{mW}$)
- Rectified demodulation: [1MHz – 20MHz]
- Stand-off distance = 20cm

Generation:
- Energy $\sim 50\text{mJ}$ / Thermoelastic regime
- NdYag pulsed laser, $\lambda=1064\text{nm}$
- Repetition rate =17Hz
- Pulse duration =10ns,
- Spot size $\sim 5\text{mm}$

![Zoom](image.png)

![FFT](image.png)

![Experiment Setup](image.png)
**Thickness measurement on moving sample**

**Sample:**
- Oxidized steel plate, 2mm thick
- Transverse velocity = 2m/s

**Detection:**
- MCRQ interferometer
- Laser ($\lambda=532$nm / 200mW)
- Rectified demodulation:
  - Bandwidth [1MHz – 20MHz]
- Stand-off distance = 20cm

**Generation:**
- Nd$^3$Yag pulsed laser $\lambda=1064$nm
- Thermoelastic regime
- Pulse duration =10ns,
- Repetition rate =17Hz
- Spot size ~5mm
Conclusions

Multi-channel random quadrature (MCRQ) interferometer

- Takes advantage of the speckle random distribution.
- Well suited for either free-space design or fiber design
- Simple and robust optical setup: No critical alignment
- Demodulation is kept very simple  ➔  Easy multi-channel integration
- Output Signals:
  - Rectified response *(High-pass filter rejects background perturbations)*
  - Linear response *(Demodulation synchronized on applied perturbations:  
  * Lock-in on reference signal  or  **Synchronization on induced Doppler)*
- Intensity noise Rejection  ➔  Built-in with linear demodulation
- Signal stability achieved through summation of multiple channels  
  (Averaging of the random process)