MICRO-ELECTRO-MECHANICAL SYSTEMS FOR CRACK MONITORING IN AGEING INFRASTRUCTURES

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Outline


- Micro-Electro-Mechanical Systems (MEMS) in crack monitoring

- MEMS fabrication

- Packaging/Assembly

- Prototyping of MEMS crackmeter and early tests
S3T Project - Underground M3

Computer vision

Aim:
Developing new methods for structural monitoring of underground infrastructures, particularly underground tunnels.

Wireless sensor networks

Project:
"Micro-measurement and monitoring system for ageing underground structures",

Coordinator:
Prof. Kenichi Soga, University of Cambridge, UK

Partners:
University of Cambridge, CNR Institute of Microelectronics and Microsystems (Italy), Technical University in Prague (Czech Republic), Universitat Politècnica de Catalunya (Spain)

Advanced simulation methods
MEMS sensors
Underground M3: distributed sensors in tunnels
Objective: MEMS wireless crackmeter

Possible design of MEMS-based wireless crackmeter

- Wall anchors
- PCB (wireless unit/sensor interface)
- Wall crack
- Silicon chip
- Steel bar
- Uniaxial strain sensors
Objective: MEMS wireless crackmeter

Crack movement analysis through uniaxial strain detection on a triangular pattern

1. Expansion
2. Contraction
3. Sliding (A)
4. Sliding (B)
Micro-Electro-Mechanical-Systems (MEMS)

1st Antisymmetric resonance mode

1st Symmetric resonance mode
MEMS resonators as strain sensors

**Resonance frequency shift**

- Axial load

**Calibrated Amplitude Spectrum [db]**

- No Strain
- 72 µstrain

**Frequency [Khz]**

-437000 to 438000

**Self-sustained oscillation at resonance**

**Strain-dependent oscillator**
Electromechanical properties of resonant MEMS

\[ R_m = \frac{2\pi m}{Q \alpha} \]

\[ \alpha = \frac{\Phi_1}{d^2} \]

\[ V_{dc} \varepsilon_0 S \]
The problem of packaging

MEMS Bonding wires

Package

Electrical connections

MEMS resonator in air (800 Torr)
- P=800T(air)
- DC=100V
- AC=-30dBm
- BW=30Hz

MEMS resonator in vacuum (3 mTorr)
- f=306.167kHz
- Q=59600
- >20dB signal

Vacuum packaging would be in principle the best solution
Objectives of MEMS activity within Underground M3

- Development of a MEMS fabrication technology for lateral resonators with coupling gaps scaled below 1 μm.

- Investigation of bonding techniques suited to fix the MEMS chip on steel with efficient strain transfer.

- Development of a vacuum packaging technique for MEMS strain sensors bonded on steel.

- Realization and test of a first prototype of MEMS-based crackmeter.
MEMS sensors fabrication: process flow

1. SOI wafer
   - Device layer: Si 15 µm
   - Handle: Si 500 µm

2. SiO₂ deposition

3. SiO₂ RIE etching

4. Polysilicon deposition

5. Oxidation

6. Oxide RIE etching

7. Scribeline etching

8. Device layer etching

9. HF vapour release

10. Metal deposition
MEMS fabrication: gap narrowing tests
MEMS fabrication – comb-drive DETF sensor
MEMS fabrication – parallel plate DETF sensor
MEMS fabrication: resonators with various geometries
MEMS fabrication: open-loop testing

Open-loop measurements on parallel-plate DETF device:

Vdc=20V, -25dBm, Signal peak > 15dB, Q>20000, f0=490kHz

Devices with high Q and low feedthrough with grounded substrate:
OK for closed-loop operation
Assembly: silicon/steel adhesive bonding

Strain sensors:
• CEA-13-250UN-120 Vishay
• 11-FA-03-120 RS Components

Experimental setup (2)
Assembly: silicon/steel solder bonding

1. Oxide etch
2. Cu evaporation
3. Pressure and heating (200 °C)
4. Foil strain gauge sticking on silicon sample
Assembly: silicon/steel strain transfer

Adhesive bonding
Strain transfer around 70 %

Solder bonding
Strain transfer above 90 %
Packaging: vacuum packaging by glass softening

Vacuum packaging technique

Measured vacuum level

Prototype

Best result with glass softening method: 300 mTorr

Problems in reliability
Packaging: vacuum packaging by soldering

Vacuum sealing with metal solder instead of glass softening

Results: improved reliability, improved vacuum level (40 mTorr)
Prototyping: crackmeter prototype with MEMS in vacuum
Prototyping: crackmeter prototype with MEMS in air

MEMS sensor

Piezoresistive sensor
Testing: crackmeter with MEMS in air

Open loop measurements on Crackmeter prototype with MUMPS round disk resonators in air.

The device shows some sensitivity to strain, but its electromechanical properties seem to be unsuitable for closed-loop operation (too large feedthrough and low peak, at least with capacitive sensing).
Testing: crackmeter with MEMS in vacuum

Crackmeter prototype assembled with vacuum packaging of a parallel-plate DETF device
Testing: crackmeter strain sensitivity

Measurements on UCAM-CNR parallel-plate resonator within the crackmeter with applied strain.

Strain sensitivity of roughly 10 Hz/µStrain, stable results with constant applied strain, reversible operation. Strain applied in the range 0-100 µStrain.
Conclusions

• A technology for the fabrication of lateral SOI MEMS resonators with good feedthrough immunity and Q up to 50,000 in vacuum has been developed.

• Strain transfer from steel to silicon has been evaluated to be around 70 % with adhesive bonding and above 90 % with solder bonding.

• A crackmeter prototype has been assembled using a vacuum-packaged parallel-plate MEMS resonator and tested with a measurement setup.

• Open-loop testing of the crackmeter was successful, with resonator Q around 9000 for Vac = 0.05 V and peak height around 20 dB. Strain sensitivity around 10 Hz/μStrain and measurement repeatability were also demonstrated using this prototype.

Future developments

• Implementation of closed-loop oscillation for the crackmeter with vacuum packaged MEMS.

• On-field testing of the crackmeter in Prague Underground.

• Implementation and testing of multi-directional strain sensing module on a new crackmeter prototype.