Long term monitoring using vibrating wire sensors

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Long term monitoring using vibrating wire sensors

- Monitoring
  - To be aware of the state of a system
    - bridge, dam, tunnel, foundation, etc.
  - To observe a situation for any changes which may occur over time using a monitor or measuring device (sensor)

- Sensors
  - Devices that detect events or changes in quantities and provide a corresponding output
Long term monitoring using vibrating wire sensors

- Generally requires sensors to be installed permanently
  - inaccessible locations
  - cannot be replaced (or re-calibrated)
  - read over the life of the construction (years)
- Therefore critical that sensors are
  - reliable (durable)
    - able to perform (correctly) for years after the installation
  - do not drift over time
    - any reading at any time can be referred to the same datum
Drift

- An inherent tendency for the value returned by a repeated measurement to vary systematically over time when there is no real variation in the parameter being measured

MOGE (UK)
Drift

“Inherent tendency for the value returned by a repeated measurement to vary systematically over time when there is no variation in the parameter being measured”

“...that any reading at any time can be referred to same datum”
Sensor retrieval possible ...

recalibration in systematic manner | correct for any drift
Sensor retrieval not possible...

critical that the sensors are reliable and do not drift
Sensor selection criteria

- Range - measurement limit of sensor
- Accuracy - how close to the “truth” (NIST standards)
- Resolution - smallest detectable increment
- Repeatability - variation in readings measured under the same conditions
- Calibration - essential if sensor readings change with time
- Environment - temperature, humidity, chemicals, pressure, accessibility...
- Duration of monitoring program - days, weeks, years
- Cost - how important are the measurements?
Sensor types

- Resistance
- Linear/Rotary Potentiometers
- LVDTs (DC DTs)
- Hall Effect Sensors
- Capacitive
- Ultrasonic
- MEMS
- Fibre Optic
- Servo Accelerometers
- T/Cs, RTDs, Thermistors, ICs
- Vibrating wire
So, why vibrating wire sensors for long term monitoring?

- Robust
  - durable
- Long term stable
  - do not drift
- Frequency output
  - can transmit signals over long cables
  - cables easily spliced
  - signals not influenced by water or moisture
- Easily datalogged
  - real time monitoring
What is a vibrating wire sensor?

1. Mechanical assembly
2. Electromagnetic excitation
3. Measurement System
How does it work?

A short pulse of current
Passes through electromagnetic coil
- near midpoint of wire
Sets the wire into transverse vibration
How does it give a reading?

- Wire oscillates in magnetic field of electromagnetic coil
- Creates a small current
  - Amplitude drops as oscillation dampens
- Travels to the readout
  - At the gage frequency
- Pulse counter measures time for “x” pulses (cycles)
- Microprocessor
  - \( T \) (period for one cycle)
  - \( \frac{1}{T} \) = frequency

Same coil is used to excite and detect the frequency of the vibrating wire.
Theory

- The law relating tension to frequency is given as
  \[ F = \frac{1}{2L} \sqrt{\sigma/r} \]  
  Where 
  \( F \) is the natural frequency of vibration, \( L \) is the length of the wire, 
  \( \sigma \) is the stress in the wire and \( r \) is the density of the wire.

- Hooke’s Law is given as
  \[ E = \frac{\sigma}{\varepsilon} \]  
  Where 
  \( E \) = Young’s Modulus, \( \sigma \) is stress and \( \varepsilon \) is strain.

- Combining (1) and (2) gives
  \[ F = k \sqrt{\varepsilon} \]  
  Where 
  \( k = \frac{1}{2L} \sqrt{AE/r} \) 
  and from which the change in strain can be shown as 
  \[ \Delta \varepsilon = k(F_1^2 - F_0^2) \]
History

• Pietro Cardani, Italy, 1858-1924
• Edward McGarvey, USA, 1899
  – (US Patent No. 633,471)
• Davidenkoff, Russia, 1928
• Andre Coyne, France, 1930
  – Telemac (France)
  – Maihak (Germany)
  – B.R.E. (London)
  – Geonor (Norway)
• Worldwide
  – USA, Spain, Korea, India, China…
Today vibrating wire sensors are manufactured in many countries...
Today vibrating wire sensors are manufactured in many countries...
Reliability of vibrating wire sensors

1. The physical durability of the sensor
   - enabling it to perform reliably years after installation

2. The time-stability of the sensor
   - that it experiences no zero drift
   - that any reading at any time can be referred to same datum
Reliability – Physical durability

• Ability to perform for years after the installation achieved by
  – materials used in construction
    • ss, Titanium, Inconel…
  – assembly procedures
    • electron beam welding, heat treating…
  – choice of signal cable
    • 100% shielded, armored, Teflon jacket…
  – cable seals
    • via bulkheads with O-rings (not epoxy)
Reliability – time stability

- 4 factors affect the time stability of vibrating wire sensors
  1. wire stress
  2. physical changes in the wire
  3. the way in which the wire is fastened in the sensor
  4. heat treating (aging)
Reliability – 1. wire stress

• Where wire stress is kept below 30% of Yield
  – zero drift is minimal
  – 1% FS after 27 years

• Where wire stress is between 13%-15% of Yield
  – zero drift is insignificant
  – 0.1% FS after 27 years
Reliability – 2. changes in the wire

• Micro-corrosion
  – reduce wire diameter and mass
  – results in an increase in resonant frequency

• Minimize the likelihood by
  – employing electron beam welding of sensor components
  – evacuating the sensor cavity
  – filling with an inert gas like nitrogen
Reliability – 3. wire fixation points

- Most important factor influencing reliability
- Poorly designed fixations
  - act as stress concentrations
  - may lead to irrecoverable strain (drift)
- Techniques are generally proprietary
  - effectiveness only proven by long term testing
    - under controlled conditions
Reliability – 4. heat treating (aging)

- Allows time for strain hardening of
  - components and fixation points
  - relaxation of internal stresses resulting from manufacturing

- Aging process can be accelerated by
  - cyclic loading/unloading
  - exposure to elevated temperatures
    - for specific periods of time
Attributes of vibrating wire sensors

• Long term stability
• Signal transmission over long cables
  – cables easily spliced
• Robustness
Long term stability

“Some Facts about Long-Term Reliability of Vibrating Wire Instruments”
Bordes & DeBreuille

Symposium on Reliability of Geotechnical Instrumentation NRC | TRB | January 1985

Piezometric level corresponding to an identical computed reservoir level reading, according to number T420 pore pressure cell

From EDF-DTG documents
Signal transmission over long cables
Cables easily spliced...
Rugged
Factors affecting vibrating wire sensors?

1. Electrical Interference (noise)
2. Temperature sensitivity
3. Damage by lightning
4. Dynamic measurements
5. Wire fatigue
6. Non-linear output
7. Advances in SOA
1. Electrical interference (noise)?

External noise corrupts the measurement of zero-crossings and returns an erroneous resonant frequency.
1. Electrical interference (noise)?

- Advances in precision of frequency measurements
- Permit analysis of vibrating wire response as a function of frequency
  - rather than as a function of time (period)
- Such spectral analysis techniques
  - discriminate the dominant frequency from any accompanying sources of electrical noise
  - provide measurement precision one order of magnitude greater than time domain based techniques
1. Electrical interference (noise)?

The analyzer “sees” the noise but it does not prevent identifying the peak spectral response & determining the wire’s resonant frequency.
2. Temperature sensitivity?

- **Vibrating wire – cold rolled 1018 steel**
  - coefficient of thermal expansion is well known \( (k_1) \)
- **Attached inside stainless steel sensor body \( (k_2) \)**
  - \( (k_1) \neq (k_2) \)
  - results in temperature dependency
- **Testing (reading) at varying temperatures**
  - Allows thermal correction to be determined
  - Correction factor provided with sensor calibration
3. Damage by lightning?
4. Dynamic measurements?

- Excitation maintains the vibrating wire in a continuously vibrating state
- 20 – 333 Hz
- Measures using spectral analysis algorithm
5. Wire fatigue?

- In any oscillating mechanical system there is always concern wrt to fatigue
- This would be of particular concern with
  - autoresonant vibrating wire sensors
  - standard versions connected to dynamic interfaces
- Testing* on vibrating wire sensors continuously vibrated over 27 years has shown
  - that fatigue failure did not occur
  - drift is minimal (<0.02% FS/year)
    - even on sensors where the wire stress is at 20% of yield

* NGI
6. Non-linear output?
6. Non-linear output?

Pressure vs Frequency$^2$

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6. Non-linear output?

![Graph of Pressure vs Frequency]
7. Advances in state of the art?

- Any sensor changes involving
  - new processes
  - different materials
- Requires time to verify its long term stability
- Recent developments
  - in materials and methods
  - stringent quality control programs
- Accelerate verification process
Vibrating wire sensor types

- Strain gages
- Displacement transducers
- Temperature sensors
- Pressure transducers
- Tiltmeters
- Force transducers
Strain gages

- Steel, concrete (HT), fibreglass (HS), soil
- Load cells, instrumented rebars & rockbolts
Pile testing
Micro-piles
Strut monitoring
Bridge truss monitoring
Measuring FRP rebar
Pressure transducers

- Piezometers (HT) (HP)
- Pressure cells
- Load cells
- Settlement systems
Multilevel (fully grouted) piezometers
Earth pressure cells
Jack-out pressure cells
Pile-tip pressure cells
Settlement systems
Displacement transducers

- Crackmeters (concrete, masonry)
- Jointmeters (mass concrete, bridge decks)
- Borehole extensometers
Construction joints
RCC dams
Geogrids
Landslide monitoring
Cable stays
Multipoint extensometer readout
Inclination sensors (tiltmeters)
Sheet pile walls
Bridge piers
Force transducers

- Precision liquid level sensors (0.07mm)
- Multipoint settlement systems
Bridge piers
Tunnels
Weirs (Seepage)
Temperature Sensors

[Diagram of temperature sensor with labels: Protective Tube, Vibrating Wire, Pluck & Read Coils, Stainless Steel Block, Cable]
Temperature Sensors

Combined VW Piezometer | VW Temperature Sensor

Temperature Sensor

Pressure Sensor
Case histories

• Dam
  – TK Dam, Rhodopes Mountains, Bulgaria | 2006-2011

• Bridge
  – Star City Bridge, PA., USA | 2003-2004

• Tunnel
  – Red Line Tunnel, Boston, MA., USA | 1999

• Highway
  – A1 Highway, Silesia, Poland | 2009-2010
TK Dam, Bulgaria

Double curved arch concrete | 130.5m Height | 480m Crest
TK Dam, Bulgaria

- 30 VW Strain gages
- 20 Pressure cells
- 66 VW Jointmeters
- 18 MPBX (3 pt)
- 20 VW Piezometers
- 12 Pendulum systems
- 6 VW Seepage weirs
- 1 Weather station
- 1 Seismic station
- Data Acquisition System

200 installed during construction
TK Dam, Bulgaria

connected to dataq system with data visualization over internet
Star City Bridge, WV, USA

306m over 4 spans | light weight concrete deck on steel girders
Star City Bridge, WV, USA

- 200 VW Strain gages
  - Steel
- 105 VW Strain gages
  - Concrete
- 42 VW Inst. rebars
- 56 VW Crackmeters
- 2 VW Displacement
- 439 Thermistors
  - Temperature
- Data acquisition
  - 6 Dataloggers
  - 20 min scan interval

850 Instruments
Red Line Tunnel, Boston, USA

Immersed tube tunnel overlying existing Red Line Subway
Red Line Tunnel, Boston, USA
Red Line Tunnel, Boston, USA
Red Line Tunnel, Boston, USA

- 700 VW Strain gages
  - & VW crackmeters
- 125 VW LL Systems
  - 1310m span
- Data acquisition system

![Image of a strain gauge and a graph showing vertical displacement caused by tides over time.]

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Red Line Tunnel, Boston, USA

![Typical vertical displacement measurements from liquid level system]

Southbound Tunnel
Settlements from 7/1/96 to 10/11/97

Northbound Tunnel
Settlements from 10/11/97 to 11/20/97

RLT Station, feet

Displacement, inches

Elev., ft.

Ft. Pt. Channel Mudline
Approx. Top of Till
Approx. Pump Room Location

RLT Crown
RLT Invert

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A1 Highway, Silesia, Poland

Geogrid stabilization of highway over area suspect to sinkholes
A1 Highway, Silesia, Poland

30,604 Instruments
Monitoring period = 30 years

- 2,541 VW Extensometers
- 12,706 VW Displacement
- 25 VW Settlement Cells
- 30 VW Inst. Rebars
- 15,247 Thermistors
  - Temperature
- Data acquisition system
  - 310 Dataloggers
A1 Highway, Silesia, Poland
A1 Highway, Silesia, Poland
A1 Highway, Silesia, Poland
A1 Highway, Silesia, Poland

- First layer of the measuring-system measurement of vertical movements of ground.
- Second layer of the measuring-system measurement of deformations of geogrid.

Highway Monitoring System
A1 Highway, Silesia, Poland

- Anchor points
- Sink Hole
- Wire Extensometers
Conclusion

• A wide variety of new and exciting sensor technologies are now available for monitoring projects of all types

• However, wherever measurements are required at locations that are
  – inaccessible after construction
  – and must operate reliably over the life of project

• Well-made vibrating wire sensors offer a reliable & cost effective solution
Thank you
Mini-Piles