

Laurent Maurin, Nicolas Roussel, Guillaume Laffont

▶ To cite this version:

Laurent Maurin, Nicolas Roussel, Guillaume Laffont. Non-intrusive pipe internal pressure measurement. NURETH19 - 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Mar 2022, Bruxelles, Belgium. cea-03687703

HAL Id: cea-03687703 https://cea.hal.science/cea-03687703

Submitted on 3 Jun2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Non-intrusive pipe internal pressure measurement

15:20-15:50, the 4th of March, 2022 – NURETH19 Workshop – Fiber-optic sensors for thermal hydraulic measurements

L. Maurin, N. Roussel & G. Laffont Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France



CEA - www.cea.fr







Non-intrusive pipe internal pressure measurement

15:20-15:50, the 4th of March, 2022 – NURETH19 Workshop – Fiber-optic sensors for thermal hydraulic measurements

L. Maurin, N. Roussel & G. Laffont Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France



CEA - www.cea.fr





Global context

- Why a non-intrusive pressure measurement ?

Non-intrusive pressure measurement and temperature compensation background

- Non-intrusive pressure measurement Background
- Temperature cross-sensitivity compensation based on the same proof body Background

► Non-intrusive pressure measurement – Underlying principle and core theory

- Underlying principle leading to temperature cross-sensitivity compensation
- The infinitely long and straight pipe under hydrostatic pressure
- The FBG transducer Some orders of magnitude
- Non-intrusive pressure ΔP_{int} measurement with direction-sensitive strain transducers
- Additional effects mitigation & application to other measurement techniques

Experimental validations – From simple to more severe conditions

- I Mechanically isolated pipe section
- II Air pressure loop
- III Water pressure loop (NPP primary coolant circuit)
 - Hot-air gun experiment to estimate the non-intrusive pressure measurement robustness
 - No fluid flow, no temperature change
 - No fluid flow, but temperature changes due to heat conduction
 - Fluid flow with massive fluid flow change (from 14 m³/h to zero) & temperature changes
- Conclusion
- Acknowledgements
- Additional information Data availability



Global context

15:20-15:50, the 4th of March, 2022 – NURETH19 Workshop – Fiber-optic sensors for thermal hydraulic measurements



6 – 11 MARCH 2022, NURETH19, BRUSSELS, BELGIUM 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics





EUROPEAN NUCLEAR SOCIETY



<u>e.g.:</u> pressure equipment directive <u>97/23/EC</u> from EU

Why a non-intrusive pressure measurement ?

- ▶ No more pipe structural health damage due to sensor installation
 - Does not require a hole per sensor
 - Measurement provided from pipe external surface, or even remotely
 - Sensors can be installed and removed on demand, without any downtime, nor requalification
- No more contact with the fluid to monitor
 - The pipe acts like the membrane of the traditional, but intrusive, sensor
 - But any undesired mechanical action on the pipe may introduce a measurement bias
 - Mitigation solution to be implemented to compensate for the effects of pure bending
- ► A crucial measurement for the oil & gas industry
 - First to prevent hydrate-plugs formation under specific **{P, T}** conditions (offshore)
 - Second to reduce the risk of pipe failure, and subsequent environmental consequences
- Non-intrusive pressure sensors development mainly driven by the oil & gas industry
 - Previous attempts mainly based on **ring sensors** (unsteady pressure), **surface strain measurements** or **acoustic waves**
 - Still suffer from shortcomings, with in general poor temperature cross-sensitivity compensation
 - Only one solution (Ekechukwu, 2021) based on both DAS and Raman DTS led to satisfactory results
- ▶ New solution applicable to any fluid transportation if pipe cross-section is circular
 - Temperature cross-sensitivity on pressure measurement intrinsically compensated / cancelled



Non-intrusive pressure measurement and temperature compensation background

15:20-15:50, the 4th of March, 2022 – NURETH19 Workshop – Fiber-optic sensors for thermal hydraulic measurements





CEA - www.cea.fr



Non-intrusive pressure measurement – Background



Diodati, **1986**, **ultrasonics** acoustic signal amplitude → dependency on fluid compressibility



Magne *et al*, **2005**, **FBG** strain rosette surface strain → temperature compensation issue → thin-shell theory approximation



Meiring *et al*, **2016**, **FBG** placed helically around the pipe surface strain → temperature compensation issue



Ekechukwu *et al*, **2021**, **DAS & Raman DTS** low-frequency DAS components → questionable if the fluid does not flow



Zhou *et al*, **2016**, **ultrasonics** propagation time of multiple longitudinal waves → temperature dependency requiring calibration → thin-shell theory approximation



Temperature cross-sensitivity compensation based on the same proof body – Background





Udd, **1995**, **overlaid FBGs** at different Schroeder *et al*, **1997** (Schlumberger[™]) wavelengths in birefringent optical fiber FBG in birefringent optical fiber





Chen et al, 2003, Hi-Bi FBG



Schlumberger™ **quartz** pressure sensor – Donzier *et al*, **2000** from "*Techniques de l'Ingénieur*", vol. E 3 093 ("*Capteurs microélectroniques*") Pressure stability better than 0.01% Full Scale / Year



FBGS™ pressure sensor based on Hi-Bi FBG https://fbgs.com/solutions/pressure-sensing/



Non-intrusive pressure measurement Underlying principle and core theory

15:20-15:50, the 4th of March, 2022 – NURETH19 Workshop – Fiber-optic sensors for thermal hydraulic measurements





CEA - www.cea.fr





Underlying principle leading to temperature cross-sensitivity compensation

Pipe behaviour under pressure well-known for decades – Formal models available

- **Materials' strength** recipes (Roark 1938) \rightarrow averaged values over pipe sections, thin vs. thick models
- Continuum mechanics in the elastic range (Love 1927, Timoshenko 1934) → full & accurate solutions derived from Airy's potential Temperature dependency to be taken into account

Exhibits different hoop *vs.* **longitudinal stress sensitivities under hydrostatic pressure**

- Balance of pipe wall internal forces vs. forces resulting from internal pressure Pint (closed pipe hypothesis)

 $(\sigma_{\theta\theta} \text{ and } \sigma_{zz} \text{ are resp. the hoop})$

& longitudinal cross-sectional

average stresses)

hoop: $2\sigma_{\theta\theta}.e.b \simeq P_{int}.2R.b$ (cylindrical cross-section balance)longitudinal: $\sigma_{zz}.e.2\pi R \simeq P_{int}.\pi R^2$ (circular cross-section balance)

 $P_{int} \simeq \frac{2\sigma_{\theta\theta}.e.b}{2R.b} \simeq \frac{\sigma_{zz}.e.2\pi R}{\pi R^2} \Rightarrow \sigma_{\theta\theta} \simeq 2\sigma_{zz} \quad \text{(thin-shell approximation)}$

- \Rightarrow In the elastic range, leads roughly to the same ratio between the *average* hoop $\varepsilon_{\theta\theta}$ and the longitudinal ε_{zz} mechanical strains, **BUT**...
 - ⇒ Poisson's transverse effect & pipe thickness do interfere significantly
 - Thin-shell model from material's strength approximation is not accurate enough to properly describe strains distribution within the pipe wall and on its surfaces "Guide de mécanique", 1998

Provides a clue for intrinsic temperature cross-sensitivity compensation with <u>orientation-sensitive</u> strain transducers by simple <u>subtraction of 2 raw measurements</u>

- Requires a complete <u>thermo</u>mechanical & accurate model
 - > Expected better efficiency than the sole Poisson's transverse effect (Maurin *et al*, 2007)
- ⇒ FBG transducers are good candidates for such implementation

temperature

compensation

paradigm different

from conventional

solutions

 $\sigma_{\theta\theta}$



The infinitely long and straight pipe under hydrostatic pressure

Elastic strains hypothesis

- Hooke's law: $[\boldsymbol{\sigma}] = 2\mu[\boldsymbol{\varepsilon}]_{mec} + \lambda \operatorname{Tr}([\boldsymbol{\varepsilon}]_{mec}) [I]$
- Hooke's law: $[\sigma] = 2\mu[\varepsilon]_{mec} + \lambda \operatorname{Tr}([\varepsilon]_{mec})[I]$ Linearized Green-Lagrange strain tensor $[\varepsilon]$ approximation: $\varepsilon_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \sum_{i=1}^{k=1} \frac{\partial u_i}{\partial x_i} + \sum_{i=1}^{k} \frac{\partial u_i}{\partial x_i} + \sum_{i=1}^{k=1} \frac{$

Problem formulated in terms of displacements

- $\vec{u} = \vec{u}_{\sigma} + \vec{u}_{T}$: total displacement \vec{u} (sum of mechanical \vec{u}_{σ} and thermal \vec{u}_{T} displacements)
- Homogeneous temperature in the pipe wall & no shear stress hypotheses \rightarrow the temperature does not generate any additional mechanical strain

Fundamental equation of dynamics for deformable bodies

div $[\boldsymbol{\sigma}] + \rho(\vec{f} - \vec{\gamma}) = \vec{0} \Rightarrow \text{div} [\boldsymbol{\sigma}] \simeq \vec{0}$ (static conditions)

set of partial differential equations

formal solution valid anywhere in the pipe wall & pipe surfaces

displacement

strain tensor

stress tensor

$$\vec{u} = f(K_1, L_1, L_2) [\mathbf{\varepsilon}] = g(K_1, L_1, L_2) [\mathbf{\sigma}] = h(K_1, L_1, L_2)$$

linear relationship with hydrostatic pressures guadratic relationship with temperature



boundary conditions applied on the straight pipe section

 K_1, L_1, L_2 are integration parameters depending on:

- pipe thermomechanical properties,
- pipe inner $r_{0_{int}}$ & outer $r_{0_{ext}}$ radiuses,
- longitudinal pulling force \vec{F} ,
- inner P_{int} & outer P_{ext} hydrostatic pressures,
- surface temperature T.



The FBG transducer – Some orders of magnitude

Temperature & strain measurements with the FBG transducer

- $\lambda_B = 2n_{eff}\Lambda \Rightarrow \frac{d\lambda_B}{\lambda_B} = (\kappa_T + \kappa_{\varepsilon}.\Delta\alpha).dT + \kappa_{\varepsilon}.d\varepsilon_{mec}$ temperature dependency mechanical strain dependency

- κ_{ϵ} . $\Delta \alpha$: additional temperature sensitivity when attached to pipe surface
 - Detached from the structure: $\Delta \lambda_B = 1 \ pm \leftrightarrow 0.1^{\circ}C \ \leftrightarrow 1 \ \mu m/m$ (@ 1550 nm)
 - Once attached to pipe surface: $\Delta \lambda_B = 1 \ pm \leftrightarrow 0.04^{\circ}C \leftrightarrow 1 \ \mu m/m$
 - Typically 2.3 times more sensitive to temperature
- Typical mechanical strain amplitude of a Ø 4" NPS Sch. 160 metallic pipe under hydrostatic pressure
 - $\Delta P_{int} = 1 \text{ bar} \Rightarrow \Delta \varepsilon_{mec} \simeq 1 \mu m/m \Rightarrow \delta P_{int} = 1 \text{ bar}$ resolution $\leftrightarrow 0.04^{\circ}C$ max temperature discrepancy

 \Rightarrow Temperature cross-sensitivity compensation is critical to reach $\delta P_{int} = 1$ bar resolution

► FBG temperature is mainly weighted by the pipe thermal effusivity

- Temperature discrepancy between 2 transducers attached to the pipe surface remains very small
- The subtraction between two raw measurements can therefore be assimilated to a purely mechanical information, in direct relationship with the internal pressure in the elastic range
 - λ₁ and λ₂ are the Bragg wavelengths of the FBG transducers attached to the pipe external surface

$$\Delta P_{int} \simeq f_{\Delta \varepsilon} (\Delta \lambda_1 - \Delta \lambda_2)$$
 $f_{\Delta \varepsilon}$: linear function

 FBG_1 \vec{u}_1 FBG_2 \vec{u}_2 \vec{v}_2

4th of March, 2022

Réseau de Bragg nº 1

Intens

Réseau de Bragg n° 2

 λ_{B1} λ_{B2} λ_{B3}

from Ferdinand, "Capteurs à fibres optiques à réseaux de Bragg", "Techniques

de l'Ingénieur", vol. R 6 735 v2, 2018

Réseau de Bragg nº 3





Non-intrusive pressure ΔP_{int} measurement with direction-sensitive strain transducers

Non-intrusive pressure measurement on a straight and closed pipe section

- Internal pressure ΔP_{int} and surface temperature ΔT variations are two independent information
 - Temperature variation ΔT also based on pipe mechanical properties (Young's modulus *E* & Poisson's ratio ν)
 - Time delayed information (due to heat diffusion) to be considered with limited confidence

$$\begin{split} \Delta P_{int} &= \Delta P_{ext} + \frac{r_{0_{ext}}^2 E\left(\underline{\Delta \Psi_1 - \underline{\Delta \Psi_2}}\right)}{\kappa_{\varepsilon} \left(1 + \nu\right) \left[\cos^2(\varphi_1) - \cos^2(\varphi_2)\right]} \left(\frac{1}{r_{0_{int}}^2} - \frac{1}{r_{0_{ext}}^2} \right) + \frac{\delta F}{\pi r_{0_{int}}^2} \\ \Delta T &= \frac{1}{\kappa_T} \left[\frac{1 - 2\nu}{1 + \nu} \frac{\underline{\Delta \Psi_1 - \underline{\Delta \Psi_2}}}{\cos^2(\varphi_2) - \cos^2(\varphi_1)} + \frac{\underline{\Delta \Psi_1 \cos^2(\varphi_2) - \underline{\Delta \Psi_2 \cos^2(\varphi_1)}}{\cos^2(\varphi_2) - \cos^2(\varphi_1)} \right) \\ &+ \frac{\kappa_{\varepsilon} \left(1 - 2\nu\right)}{E} \Delta P_{ext} - \frac{1}{\pi E} \frac{2\kappa_{\varepsilon} \left(1 - \nu\right)}{r_{0_{ext}}^2 - r_{0_{int}}^2} \delta F \right] \\ \bullet \text{ Bending mitigation by simple averaging} \\ \bullet \text{ Requires } N \geq 2 \text{ sensors evenly distributed in ring position around the pipe} \\ \Delta P_{int} &= \Delta P_{ext} + \frac{r_{0_{ext}}^2 E\left[\frac{1}{N}\sum_{k=1}^{k=N} \left(\underline{\Delta \Psi_{1k} - \underline{\Delta \Psi_{2k}}\right)\right]}{\kappa_{\varepsilon} \left(1 + \nu\right) \left[\cos^2(\varphi_1) - \cos^2(\varphi_2)\right]} \left(\frac{1}{r_{0_{int}}^2} - \frac{1}{r_{0_{ext}}^2}\right) + \frac{\delta F}{\pi r_{0_{int}}^2} \\ \Delta T &= \frac{1}{\kappa_T} \left[\frac{1 - 2\nu}{1 + \nu} \frac{1}{\cos^2(\varphi_2) - \cos^2(\varphi_1)} + \frac{1}{N} \sum_{k=1}^{k=N} \left[\underline{\Delta \Psi_{1k} \cos^2(\varphi_2) - \underline{\Delta \Psi_{2k}} \cos^2(\varphi_1)\right]}{\cos^2(\varphi_2) - \cos^2(\varphi_1)} \right) \\ &+ \frac{\kappa_{\varepsilon} \left(1 - 2\nu\right)}{E} \Delta P_{ext} - \frac{1}{\pi E} \frac{2\kappa_{\varepsilon} \left(1 - \nu\right)}{r_{0_{ext}}^2 - r_{0_{int}}^2} \delta F \right] \\ &+ \frac{\kappa_{\varepsilon} \left(1 - 2\nu\right)}{E} \Delta P_{ext} - \frac{1}{\pi E} \frac{2\kappa_{\varepsilon} \left(1 - \nu\right)}{r_{0_{ext}}^2 - r_{0_{int}}^2} \delta F \right] \\ &+ \frac{\kappa_{\varepsilon} \left(1 - 2\nu\right)}{E} \Delta P_{ext} - \frac{1}{\pi E} \frac{2\kappa_{\varepsilon} \left(1 - \nu\right)}{r_{0_{ext}}^2 - r_{0_{int}}^2} \delta F \right] \\ &+ \frac{\kappa_{\varepsilon} \left(1 - 2\nu\right)}{E} \Delta P_{ext} - \frac{1}{\pi E} \frac{2\kappa_{\varepsilon} \left(1 - \nu\right)}{r_{0_{ext}}^2 - r_{0_{int}}^2} \delta F \right] \\ &+ \frac{\kappa_{\varepsilon} \left(1 - 2\nu\right)}{E} \Delta P_{ext} - \frac{1}{\pi E} \frac{2\kappa_{\varepsilon} \left(1 - \nu\right)}{r_{0_{ext}}^2 - r_{0_{int}}^2} \delta F \right] \\ &+ \frac{\kappa_{\varepsilon} \left(1 - 2\nu\right)}{E} \Delta P_{ext} - \frac{1}{\pi E} \frac{2\kappa_{\varepsilon} \left(1 - \nu\right)}{r_{0_{ext}}^2 - r_{0_{int}}^2} \delta F \right] \\ &+ \frac{\kappa_{\varepsilon} \left(1 - 2\nu\right)}{E} \Delta P_{ext} - \frac{1}{\pi E} \frac{2\kappa_{\varepsilon} \left(1 - \nu\right)}{r_{0_{ext}}^2 - r_{0_{int}}^2} \delta F \right] \\ &+ \frac{\kappa_{\varepsilon} \left(1 - 2\nu\right)}{E} \Delta P_{ext} - \frac{1}{\pi E} \frac{2\kappa_{\varepsilon} \left(1 - \nu\right)}{r_{0_{ext}}^2 - r_{0_{int}}^2} \delta F \right] \\ &+ \frac{\omega_{\varepsilon} \left(1 - 2\nu\right)}{E} \Delta P_{ext} - \frac{1}{\pi E} \frac{2\kappa_{\varepsilon} \left(1 - \nu\right)}{r_{0_{ext}}^2 - r_{0_{int}}^2} \delta F \right] \\ &+ \frac{\omega_{\varepsilon} \left(1 - 2\nu\right)}{E} \Delta P_{ext} - \frac{1}{\pi E} \frac{2\kappa_{\varepsilon} \left(1 - \nu\right)}{r_{0_{ext}}^2 - r_{0_{int}}^2} \delta F \right] \\ &+ \frac{\omega_{\varepsilon} \left($$



Additional effects mitigation & application to other measurement techniques

The subtraction compensation process leads to a <u>purely mechanical information</u>

- Temperature influence on pressure measurement is intrinsically cancelled
 - Transducers sensitivity to temperature must be equal
- Any additional effect, different from purely mechanical, should also be optimally mitigated
 - *e.g.*: nuclear radiations influence on FBGs (responsible for Bragg wavelength shifts)
- The temperature ΔT information should therefore be considered as a global influence parameter
 - Including temperature, but also any additional non-mechanical influence on the transducers

► Application to other direction-sensitive surface <u>strain</u> or <u>length</u> measurement techniques

The longitudinal mechanical strain variation $\Delta \varepsilon$ is nothing else but a relative length variation

$$\Delta \varepsilon = \ln \left(1 + \frac{\Delta L}{L} \right) \sim_{0} \frac{\Delta L}{L} \quad \text{(true longitudinal strain variation definition)}$$

- Every measurement technique capable to measure length variations ΔL on pipe surface should also be able to perform non-intrusive pressure measurement
- Examples of candidate measurement techniques:
 - Ultrasonics with PZT transducers
 - Non-contact cross-correlation technique with video cameras for remote pressure monitoring (if sensitivity OK with regards to strain ranges)



example of PZT transducers configuration distributed on pipe surface & dedicated to non-intrusive temperature self-compensated pressure measurement



Experimental validations – From simple to more severe conditions

15:20-15:50, the 4th of March, 2022 – NURETH19 Workshop – Fiber-optic sensors for thermal hydraulic measurements





CEA - www.cea.fr



Technip Energies, Marseille, FR

July 2019

I – Mechanically isolated pipe section

Pipe section filled with pressurized water

- No external force applied on the pipe Room temperature
- Inflating pressure up to 300 bar
- Pipe length greater than 5 times its diameter
 - FBG transducers in the middle of the pipe section to be free from side effects



one non-intrusive FBG-based pressure sensor made of two FBG transducers in hoop and longitudinal configurations (best sensitivity configuration, also insensitive to torsion)



TECHNIP

ENERGIES

T.EN

non-intrusive pressure measurement error **better than 0.54% Full Scale** at 2 σ after calibration – **5 Hz** measurement rate A_{cal} : calibration scale factor (*i.e.*: the gauge factor) B_{cal} : calibration pressure offset

measurement performed without delay (in real-time)



II – Air pressure loop

cea

CEA, DES, Mercure facility, Cadarache, FR IRESNE, Research Institute for Nuclear Systems for Low Carbon Energy Production October 2019

- Air pressure loop including several bends
 - FBG transducers in the middle of a 5 m long pipe section Complex pipe layout with many bends
 - Air flow rate steps up to 300 m^3/h Room temperature

complex pipe layout including several bends and attachments



one non-intrusive pressure sensor made of two FBG transducers in hoop and longitudinal configurations (best sensitivity configuration, also insensitive to torsion)

thermocouples on pipe surface for reference temperature

RosemountTM air flow rate *Q*: $Q_{[m^3/h]} = 3600 \times (0.02661 V_{[V]} - 0.02778)$







III – Water pressure loop (NPP primary coolant circuit)



CEA, DES, BEARN 2 facility, Saclay, FR 2020

- ▶ BEARN 2 water pressure loop (up to 320°C 150 bar 14 m³/h)
 - FBG transducers installed on Ø 2" NPS Sch. 80 and Ø 4" NPS Sch. 160 pipe sections
 - Non-intrusive sensors made of pairs of FBG transducers in hoop & longitudinal configurations
 - Rings configurations to mitigate bending effects



Ø 2" NPS Sch. 80

typical pipe attachment

Ø 4" NPS Sch. 160

Typical orders of magnitude (see also page 12)

Ø 4'' NPS Sch. 160 vs. Ø 2'' NPS Sch. 80 steel pipes			ø 4''	ø 2''
$\Delta P_{int} = 100$ bar	\Rightarrow	$\Delta \varepsilon_{ heta heta_{mec}} - \Delta \varepsilon_{zz_{mec}}$	93.4 µm/m	133 µm/m
1 pm measurement error	\Rightarrow	pressure measurement error δP_{int}	0.89 bar	0.62 bar
1°C temperature compensation error	\Rightarrow	pressure measurement error δP_{int}	26.6 bar	18.6 bar
1 bar pressure resolution	\Rightarrow	temperature compensation better than	0.038°C	0.054°C
1 bar pressure error	\Rightarrow	unexplained longitudinal force variation δF	600 N	190 N





III – Water pressure loop (Ø 4" NPS Sch. 160 section)



CEA, DES, BEARN 2 facility, Saclay, FR 2020

Hot-air gun experiment to estimate the non-intrusive pressure measurement robustness

- Measurements performed on Ø 4" NPS Sch. 160 metallic pipe section
- Hot-air temperature estimated greater than 100°C to generate asymmetrical temperature distribution around the pipe (hot spot)
- Typically 5 cm distance between FBG transducers in hoop & longitudinal configurations
 - Temperature difference between FBG transducers estimated greater than 40°C



CEA L. Maurin, N. Roussel & G. Laffont – Original paper available at: https://www.frontiersin.org/articles/10.3389/fsens.2022.835140

- pressure calibration performed **during** important flow ΔQ and temperature ΔT changes
- FBG pressure average error during calibration close to **2 bar** (2 σ)
- similar FBG surface temperature evolution than reference sensor

bending mitigation with 2 FBG-based sensors (\Rightarrow 2x2 = 4 FBGs) in ring configuration

⇒ maximum pressure error roughly reduced by a factor of two vs. single sensor measurement, from -8.6 bar to -5 bar

massive flow change, combined with fluid flow direction changes (bends), may generate significant bending forces \vec{F} on the pipe

CEA, DES, BEARN 2 facility, Saclay, FR

2020

Cez

Conclusion

15:20-15:50, the 4th of March, 2022 – NURETH19 Workshop – Fiber-optic sensors for thermal hydraulic measurements

CEA - www.cea.fr

Cea

Conclusion

- Optimal temperature cross-sensitivity compensation is a key parameter for a reliable pressure measurement
- The closed pipe with circular cross-section provides an intrinsic mean to compensate for the transducers temperature cross-sensitivity with the same proof body
 - The subtraction of two true relative raw measurements of direction-sensitive strain transducers is a purely mechanical information
 - Demonstrated by the linearized formal model for pipes with circular cross-section
 - Can probably be extended to other pipe cross-section shapes, but much more complicated to establish a dedicated formal model for demonstration...
 - In the elastic range, this information is proportional to the pipe internal pressure variation ΔP_{int}
 - The pipe surface temperature variation ΔT is an additional, but time delayed (due to heat diffusion in the pipe wall) information provided by the formal model, independently from the pressure information
- ► Any additional non-mechanical effect can theoretically be intrinsically compensated
 - e.g.: nuclear radiations on Bragg wavelengths for FBG transducers (but additional work necessary...)
- Can be extended to any direction-sensitive surface strain or distance measurement
 - Ultrasonics with PZT transducers
 - Non contact cross-correlation techniques (remote sensing)
- Opens the way to new kinds of temperature self-compensated hydrostatic pressure sensors, based on a closed proof body with circular cross-section
 - From tens to hundreds of bar in pressure ranges (depending of proof body mechanical properties and dimensions)

example of new kind of temperature self-compensated hydrostatic pressure sensor for *external* pressure P_{ext} monitoring

Acknowledgements

Additional information – Data availability

ENS

CEA - www.cea.fr

Acknowledgements

- M. Daniel Mabily from Technip Energies for the kind permission to publish the data and the results from the pressure test held in Marseille in July 2019
- M. Kévin Cruz from CEA DES IRESNE for the pressure test held on Mercure facility in Cadarache in October 2019
- M. Franck Ruffet from CEA DES DM2S for his availability during the pressure tests held on BEARN 2 facility in Saclay in 2020
- ► The **FSH public fund** which permitted to initiate the work on the formal model
- M. Marc Baqué and TotalEnergies which co-funded this research topic for a solution based on a different principle, but enabled us to benefit from the upgraded BEARN 2 pressure loop facility for this sensor
- Prof. Patrice Mégret from the University of Mons for the invitation to NURETH19 workshop

25

Additional information – Data availability

- This topic is published in *Frontiers in Sensors*, "Recent Advances in Optical Fiber Sensors"
 - https://www.frontiersin.org/research-topics/23029/recent-advances-in-optical-fiber-sensors
 - Original paper available at: https://www.frontiersin.org/articles/10.3389/fsens.2022.835140

Articles scientifiques du CEA

🛃 frontiers

Optimally temperature compensated FBG-based sensor dedicated to non-intrusive pipe internal pressure monitoring

Laurent Maurin 1.*. Nicolas Roussel 1 and Guillaume Laffont

¹Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France Correspondence* Laurent Maurin

Optic Fiber Sensors Laboratory, Metrology, Instrumentation and Information Department, List Institute, PC 72, CEA/Saclay, F-91191 Gif-sur-Yvette, France laurent.maurin@cea.fr

ABSTRACT

Pipe internal pressure measurement is of utmost importance in the oil & gas industry to monitor the extraction process, and thus to prevent hydrate-plugs formation which may occur in specific temperature & pressure conditions. Traditional solutions usually rely on pressure sensors in direct contact with the fluid to monitor, therefore requiring one hole per sensor, but they also weaken the pipe structure, which may prematurely lead to significant leaks. Attempts to develop non-intrusive pressure sensors relying, for instance, on acoustic waves detection or even strain measurements (the pipe wall acting, in some way, like the membrane of a traditional intrusive sensor), are up to now not fully satisfying, mainly due to poor temperature cross-sensitivity compensation. Thus, 1 °C temperature compensation error typically leads for Fiber Bragg Grating (FBG) transducers to pressure measurement biases greater than 26%@100 bar (e.g.: ø 4" NPS Sch. 160 steel pipe). Consequently, if such non-intrusive, but biased, solutions could possibly have been considered to monitor, for instance, a Nuclear Power Plant (NPP) primary coolant circuit, it was with the risk of dramatic consequences since the fluid can reach temperatures up to 320 °C. On the other hand, the solution detailed here truly achieves to cancel the temperature cross-sensitivity, and potentially any additional effect on pressure measurement, provided that each effect has the same influence on all transducers. It first relies on a better understanding of the pipe behavior under hydrostatic pressure, supported by a dedicated model developed on purpose, which demonstrates that the internal pressure & the surface temperature variations of a closed pipe can be recovered with at least two direction-sensitive transducers, the temperature dependence of the pressure measurement being simply removed by a straightforward compensation process. This paper explains the underlying principle, thanks to a formal model established with only few hypotheses, but extended to more complex field conditions. It ends with a lab-test validation involving FBG transducers attached to a pressure circuit submitted to temperature variations greater than several tens of °C, and concludes about the advantages & limitations of this novel approach for non-intrusive sensing, and its potential extensions to other measurement techniques.

rords: non-intrusive measurement, hydrostatic pressure, pipe, oil & gas, intrinsic temperature comp ection-sensitive transducer, Fiber Bragg Grating

Optimally temperature compensated FBG-based sensor dedicated to

Pipe internal pressure measurement is of utmost importance in the oil & gas industry to monitor th

extraction process, and thus to prevent hydrate-plugs formation which may occur in specific temperature & pressure conditions. Traditional solutions usually rely on pressure sensors in direct contact with the fluid to monitor, therefore

quiring one hole per sensor, but they also weaken the pipe structure, which may prematurely lead to significant leaks

regulting one hole set restor. Due they also vesame the pipe structure, which may premuturely task to adjoritude tasks. Harmst to device non-intrusive presence sensors reliving, non-intrusive, na accurate tasks to adjoritude tasks of May staffysts, makely due to goot temperature consensation? The comparison of the pipe wall acting, in some way, like the membrane of a stafficial intrusive sensor), are up to now the May staffysts, makely due to goot temperature consensativity comparison. Thus, 17-00 temperature sensors and the staff of the membrane of a stafficial intrusive sensors. The sensors than 240-900 bits (rs.) GPV MS Sch. 360 steel giels). Consequently, if advortment to the bitset, stations could be advorted to the sensors with the sensors and the sensors that (1900) privary could crucicity. It was with the risk of dramatic consequences since the fluid can erack temperature to to 320°C. On the ther hand, the solution solution of the pipe behavior under hydroxitic pressure, supported by a dedicated model developed on purpose, which demonstrates that the literal pressure. It has simple memory to a dedicate model developed on purpose, which demonstrates that the literal pressure. The temperature dependence of the pressure measurement being might removed by a staffightment comparison pressure to a structure variations greater than test variation involving Fillic transforms statules to a server toricit structure variations greater the serveral test of c-na concidered as one fillic developed on purpose.

several tens of °C, and concludes about the advantages & limitations of this novel approach for non-intrusive sensing

Physique [physics] / Physique [physics] / Instrumentations et Détecteurs [physics.ins-det iclences de l'ingénieur (physics) / Optique / photonique iclences de l'ingénieur (physics) / Traitement du signal et de l'image [eess.SP] ciences de l'ingénieur (physics) / Mécanique (physics.med-ph) / Matériaux et structures en mécaniqu

non-intrusive sensor Hydrostatic Pressure Pipe Oli & gas Surface temperature

sducer FBG sensor experimental validation Pressure Loop Optical Fiber Sensor Fiber Bragg Grating Distributed and Quasi-distributed sensing

mperature compensation bending mitigation Formal model Iterative algorithm

non-intrusive pipe internal pressure monitoring

LCFO - Laboratoire Capteurs Fibres Optiques
DM21 - Département Métrologie Instrumentation & Information : DRT/LIST/DM21

Laurent Maurin 1, Nicolas Roussel 1, Guillaume Laffont 1

and its potential extensions to other measurement technique

Type de document : Article dans une revue

hysics.class-ph1

CQ2

Open data will be made available in the CEA HAL open archive:

https://hal-cea.archives-ouvertes.fr/cea-03541365

HAI

HAL Id : cea-03541365, version 1
DOI : 10.3389/fsens.2022.835140

CEA | DRT | LIST | DM21 | GS-ENGINEERING | CEA-UPSAY | GS-COMPUTER-SCIENCE

Laurent Maurin, Nicolas Roussel, Guillaume Laffont,

BibTeX TEI DC DCterms EndNote

Consultations de la notice

12

f У 🖻 +

nerature compensated FRG-based ensor dedicated to non-intrusive pipe internal ressure monitoring. Frontiers in Sensors, Frontiers ledia, In press, (10.3389/fsens.2022.835140). (cei

much more information about this sensor can be found in this article

this presentation will also be made available in the CEA HAL open archive

CEA L. Maurin, N. Roussel & G. Laffont - Original paper available at: https://www.frontiersin.org/articles/10.3389/fsens.2022.835140

26

Thank you for your attention

L. Maurin, N. Roussel & G. Laffont Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France

Credits: some of the pictures of this presentation are available under the Creative Commons Attribution License (CC BY)

CEA - www.cea.fr