**Motivation**

Strain level estimation – Lifetime determination – Fatigue

Different methods for the determination of strain levels → Different results

Validation and verification of the strain levels

Finite Elements Method (FEM)  Strain Gauge Measurements (SGM)

Link?
Motivation

What is the real strain$^1$? How can we verify the strains?
What are the biases and uncertainties?

$^1$ Guide to the expression of uncertainty in measurement (GUM), 2008, International Organization for Standardisation
Strain gauge uncertainties

- Uncertainty sources reviewed in literature\textsuperscript{1,2} → Gauge factor, alignment error, temperature, measuring device, hysteresis, integration error...

- Uncertainties studied:
  - Positioning uncertainties
  - Gauge behavior
  - Transverse sensitivity

- Use of the FE model: estimation of the displacement fields (spatial variation)

Proposed method

METHOD

1) Creation of numerical gauges on the FE model, with random positioning errors

2) Estimation of the strains measured by the gauges from FE displacement fields, taking in account their uncertainties
Proposed method

METHOD

A gauge is an electrical wire glued on the part. When the part deforms, the
gauge deforms in the same way, varying its electrical resistance.

\[
\frac{dR}{R} = \frac{K}{1 - \nu_0 K_t} (\varepsilon_l + K_t \varepsilon_t)
\]

\[
\varepsilon_{Lj} = \frac{L_L - L_{L0}}{L_{L0}} = \frac{\left[ (L_{L0} + (\overrightarrow{U_{L2}} - \overrightarrow{U_{L1}}) \cdot \overrightarrow{X})^2 + \left( (\overrightarrow{U_{L2}} - \overrightarrow{U_{L1}}) \cdot \overrightarrow{Y} \right)^2 \right]^{0.5} - L_{L0}}{L_{L0}}
\]

\[
\varepsilon_{Tk} = \frac{L_T - L_{T0}}{L_{T0}} = \frac{\left[ (L_{T0} + (\overrightarrow{U_{T2}} - \overrightarrow{U_{T1}}) \cdot \overrightarrow{Y})^2 + \left( (\overrightarrow{U_{T2}} - \overrightarrow{U_{T1}}) \cdot \overrightarrow{X} \right)^2 \right]^{0.5} - L_{T0}}{L_{T0}}
\]
Proposed method

METHOD

A gauge is an electrical wire glued on the part. When the part deforms, the gauge deforms in the same way, varying its electrical resistance.

\[
\frac{dR}{R} = \frac{K}{1 - \nu_0 K_t} (\varepsilon_l + K_t \varepsilon_t)
\]

\[
\bar{\varepsilon}_L = \frac{\Sigma_{j=1}^{n} \varepsilon_{Lj}}{n}
\]

\[
\bar{\varepsilon}_T = \frac{\Sigma_{k=1}^{2} \varepsilon_{Tk}}{2}
\]

\[
\bar{\varepsilon}_{VG} = \frac{1}{1 - \nu_0 K_t} (\bar{\varepsilon}_L + K_t \bar{\varepsilon}_T)
\]
Proposed method

Estimation of the strain distribution that should be measured by gauges placed on the FE model, taking in account biases and uncertainties of the gauges

METHOD

Input generation → Monte Carlo Simulations → Strain distribution

- Generation of numerical gauges on the FE model
- Estimation of the strain, including uncertainties
Proposed method

Estimation of the strain distribution that should be measured by gauges placed on the FE model, taking in account biases and uncertainties of the gauges

METHOD

Motivation – Uncertainties – Proposed Method – Validation – Application – Conclusion
Experimental validation

- 2 specimens in tension - compression
- Rosettes and welded gauges – significant biases obtained depending on the gauges (measures from -700 to -800 με for an analytical strain of -800 με)

Correlation: experimental measures / strain obtained with the proposed method

\[ \bar{R} = 0.9764 x + 3.7312 \]
Experimental validation

- Correlation FE Strain / Measurement Strains and Method / Measurement for different gauges

**BEFORE**

FE Strains vs Experimental Strains

- The method corrects the FE strains to take in account the biases and uncertainties of the gauges
  
  \[ \text{A better coefficient of correlation} \]

**AFTER**

Method Strains vs Experimental Strains
Proposed method application

- Application on a Francis turbine
- 10 welded gauges placed on 2 blades
- Differences between the FE strains and experimental measurements
- Can it be explained by the welded gauge uncertainties?
Application results

- Significant biases and uncertainties obtained

- Validation of the FE model with the strain gauge uncertainties?

![Relative strains by location](image)

- Strain distribution obtained with our numerical method
- FEM strain at target location (Ref.)
- Measurement range

Motivation – Uncertainties – Proposed Method – Validation – Application – Conclusion
Conclusion

- Development of a numerical method to estimate strain gauge biases and uncertainties

- Allows the cross-validation of the FE model with strain gauge measurements

- Experimental validation of the method

- Application on a Francis turbine

- Permits the optimisation of the measurement parameters (type of gauge, location…)

- Could be applied with other sensors

Thank you for your attention!

Questions ??

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