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A STUDY OF THE STABILITY, RELIABILITY, AND ACCURACY OF NEUBRESCOPE-BASED PIPE THINNING DETECTION SYSTEM

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Abstract

This paper presents a robust pipe thinning detection method, built upon the *Neubrescope* fiber sensing technology. The *Neubrescope* is the only commercially available high precision, cm-order Distributed Temperature and Strain Sensing (DTSS) system, employing the Stimulated Brillouin Scattering (SBS).

This work discusses in detail the uncertainty and accuracy of the measurement data and examines the influences of factors like polarization average, relative instability of the pump and probe laser, frequency-scanning step, BGS data fitting algorithms, noise ratio, self-calibration, as well as methodological errors, on the measurements. Results of both theoretical analysis and experimental validation are presented. Furthermore, the paper outlines, the inverse analysis algorithm, utilizing the measurements data obtained by means of *Neubrescope* optical fiber sensing system. The strain values in the fiber are used to detect shape, location, and depth of the pipeline thinning. The algorithm implements the *Boundary Element Method* (BEM) [1], sensitivity analysis, and full 3D structural model. All required numerical enhancements, advantages, and drawbacks of this approach are also presented. The results of series of tests are included, demonstrating the high accuracy and reliability of the sensing system, as well as the stability, and robustness of the numerical algorithms.

INTRODUCTION

An early detection and monitoring of pipe thinning is of crucial importance in engineering and technological practice, especially in highly pressurized and/or in containing hazardous substances pipelines. The technique considered nowadays as a standard procedure for inspecting pipeline thickness is the Ultrasonic Technology (UT). The UT measurements, however, require removing the pipe insulation, usually stopping the technological process, and thus being very expensive to carry out. A priori selected, limited in size, portions of the pipe are scanned only, but it does not give a complete view of the pipe condition. An alternative approach is offered by an optical fiber distributed sensing, which provides strain measurements. In the latter, the high spatial resolution is a primary requirement as the effect of thinning on deformation pattern (and strain field) is localized. The information on current thickness of the pipe must be recovered (calculated) from the measured strains based on an appropriate structural model of the pipe. Typically, one-dimensional models are employed, yielding analytical solutions. This results, at best, in underestimating depth of pipe thinning, as the uniform (averaged) thickness can be obtained, only, while the size and exact location of thinning are never detected. Also approximation of boundary conditions may be, in the case of 1D model, very questionable. The more accurate estimation of pipe thinning can be achieved using the full 3D models, with arbitrarily imposed boundary conditions. To solve these types of models, numerical methods are almost exclusively used. The procedure utilized in this work applies to the *Boundary Element Method* (BEM) [1]. As the location and shape of the thinning are unknown, the solution procedure involves iterations, where the new thinning position and size are estimated based on minimizing the prescribed objective function and the geometry of the domain it becomes updated. It should be emphasized that because BEM requires discretization of the surfaces only, re-meshing due to modification of the position of a thinning area is not an intricate task. This makes the calculation straightforward and considerably easier comparing to other numerical methods, also avoiding entirely, problems with mesh distortion. On the other hand, due to relatively small thickness of the pipe, special numerical algorithms for *nearly singular integration* of surface elements must be employed, in order to ensure its high accuracy.

The primary objective of this research is to develop and verify an algorithm for estimation of the pipe thinning using the optical fiber measurement data. In this paper, we present a method built upon the *Neubrescope* sensing system. The Neubrescope is the only commercially available high precision Distributed Temperature and Strain Sensing (DTSS) system, employing the Stimulated Brillouin Scattering (SBS). It is also capable of providing highly accurate and of cm-order spatial resolution data. The repeatability and reliability of measurements are examined in detail. The influence of polarization average, frequency-scanning step, as well as self-calibration is studied. The pipeline test model is then used to validate the BEM-based inverse analysis method. Its accuracy, convergence, and robustness are demonstrated.

PROBLEM FORMULATION

The mathematical model of thermoelastic deformation within an arbitrary domain, Ω, enclosed by boundary, Γ, contains a set of partial differential equations, describing the temperature and stress fields. Combining the equilibrium and constitutive equations, neglecting body forces, and assuming linear strain-displacement relationship, steady-state deformation in isotropic solids, can be described by Navier's equations in the following form:

$$\mu u_{j,ii} + (\lambda + \mu) u_{i,ji} - (3\lambda + 2\mu)\delta_{ij}\alpha\theta = 0 \qquad (1)$$

where σ, ε, and u, stand for stress, (total) strain, displacement, respectively, while α, δ, μ, λ denote coefficient of thermal expansion, Kronecker's symbol, Lame's constants. The temperature difference, θ, is given as:

$$\theta \equiv T - T_{ref} \qquad (2)$$

where T and T_{ref} are the actual temperature and reference (stress-free) temperature, respectively. In the foregoing and all of the following equations, Einstein's summation convention is applied for repeated indices and the comma denotes the partial derivative with respect to spatial coordinates. Equations (1)-(2) with boundary conditions:

$$u(\mathbf{x}) = \bar{u} \qquad \mathbf{x} \in \Gamma_u \qquad (3)$$

$$t(\mathbf{x}) = \bar{t} \qquad \mathbf{x} \in \Gamma_t \qquad (4)$$

where

$$t_i = \sigma_{ji} n_j \qquad (5)$$

and $\Gamma_u \cup \Gamma_t = \Gamma$ constitute the well-posed boundary-value problem. In (5) t_i denotes the boundary traction, with n being the outward normal vector. The differential equation (1) is most frequently solved using numerical methods, namely, the *Finite Element Method* (FEM) or *Boundary Element Method* (BEM), which transforms it to the set of linear algebraic equations.

In the problems of thinning detection considered in this paper, the shape of portion of the boundary is unknown (and also its location is not specified), usually due to corrosion, defects or any other reasons. It means that, the set of boundary equations (3)-(4) is incomplete, and a mathematical model cannot be solved using conventional methods. However, providing the additional information, in the form of measurements, allow one to solve the model and thus to estimate the position and shape of thinning. Unfortunately, the influence of thinning on strain field is usually localized and it appears most frequently at internal, inaccessible surface of the pipe, posing substantial numerical challenges for the solution procedures. The key factor in successful identification of thinning is the large data set, containing highly accurate, of high spatial resolution measurements. In the next Section, we examine uncertainty of strains measurements offered by the *Neubrescope* sensing system.

MEASUREMENT DATA UNCERTAINTY

The *Neubrescope* sensing system uses an innovative *Pre-Pump-Pulse Brillouin Optical Time-Domain Analysis* (PPP-BOTDA) [2, 3] to measure strain and/or temperature in the optical fiber. As in the BOTDA family of methods, two laser beams, a pump pulse and a continuous wave (CW) probe light, are injected into optical fiber (from both its ends), that interacts and excites acoustic waves in it. The pump pulse is, then, backscattered by the phonons, and part of its energy is transferred to the CW. This results in the CW power gain, called the Brillouin Gain Spectrum (BGS), which is a function of frequency differences of the two laser beams and it can be measured at the output end of the probe light. The peak frequency of the BGS spectrum is used to estimate the fiber strain or temperature, while its position is calculated from the light round-trip time. Both of these values, that is, strain/temperature location and its magnitude are subject to measurements uncertainties.

The uncertainties are related to many aspects of the hardware design and implementation, as well as the measurement method used. Some of them are beyond control, especially in real-life, commercial implementations and their influence is only minimized by proper design and other special measures. Table 1 summarizes all factors influencing the accuracy of measurements for the current version of *Neubrescope* system.

Table 1. Factors influencing accuracy of the Neubrescope sensing system

Factor	Influence on		Source and reason
	accuracy	repeatability	
1. Relative stability of the pump and probe laser	strong	strong	hardware related
2. FWHM of BGS	direct	slight	80 MHz (by design)
3. S/N of BGS	direct	direct	fiber quality and settings related
4. Step of frequency scanning	direct	direct	measurement time dependent
5. Fitting to BGS data	slight	slight	fitting function and S/N
6. Methodological error	slight	negligible	induced by PPP method

One of the most important factors is the relative instability of the pump and probe lasers (Table 1, point 1), and is mainly a result of thermal shift within electronic hardware components. Currently, it can be (hardware) controlled and decreased to ± 2.5 MHz. The *Neubrescope* system also implements the reference fiber, allowing one to calibrate the BGS peak frequency, further reducing the instability to just 0.7 MHz. The signal-to-noise ratio (S/N) can be improved mainly by increasing the number of averages, which is clearly seen from Table 2. Influence of factors four and five (Table 1), can be significantly reduced by decreasing the step size. However, due to the influence of pump and probe laser instability (point 1), it will bring no effect for steps below 1 MHz.

The carefully designed synchronization mechanism (PXI frame), decreases the uncertainty of time measurement to less than 10 picoseconds, which corresponds to a distance of less than 1 mm.

Table 2. Number of averages and its influence on repeatability

No. of averages	Frequency step	Repeatability
10^{13}	5 MHz	±2.5 MHz (± 50 με)
10^{14}	5 MHz	±2.1 MHz (± 42 με)
10^{15}	5 MHz	±1.8 MHz (± 36 με)

The PPP-BOTDA method itself introduces a methodological error of a slight influence on accuracy of measurements, which depends on the specific strain pattern; however, in any case, it should not exceed 25 με. The presented theoretical analysis was validated on numerous experimental tests carried out at *Neubrex*. In all experiments, the Gaussian distribution of errors, with zero mean value, was obtained and typical standard deviation as high as 15 με achieved.

All that confirms that *Neubrescope* sensing system can be used for high precision, long-term strain measurements in a wide range of applications. The large number of measurements assists in isolating the localized hazards in the monitored system, leading to global-local analysis, and sub-structuring, which is of crucial importance in real-life, engineering problems.

INVERSE ANALYSIS

Inverse analysis attempts to detect both the location and the shape of the pipe thinning, by minimizing the objective function, *I*, defined as the norm of differences between measured, $\bar{\varepsilon}_f$, and calculated, $\bar{\varepsilon}_c$, strains along the fiber path:

$$I = \left\| \bar{\varepsilon}_f - \bar{\varepsilon}_c \right\|^2 \qquad (6)$$

The measured strains are given as their magnitudes in the tangential direction along a fiber path in the *moving average* sense [4]. The calculated strains are obtained from structural model, and are a function of unknown thinning shape. In order to decrease the number of unknowns (and thus increase stability of inverse analysis), the thinning shape is parameterized. Typical, corrosion based pipe thinning can be approximated by ellipsoidal shape, and thus requiring five to seven parameters (as the location is also unknown). Here, for the sake of clarity of a presentation, we assume that all remaining boundary conditions are given. However, in most of the engineering applications part(s) of boundary conditions (3)-(4), is also unknown, and it needs to be estimated using inverse analysis as well. In this situation, the large number of strain data provided by *Neubrescope* sensing system is especially useful, allowing one to use global-local modeling approach and to estimate the required BC from the same data set.

As the measured strain is provided as its moving average, the calculated strain tensor values need to be transformed:

$$\varepsilon_c = g_i \varepsilon_{ij} g_j \qquad (7)$$

and then averaged:

$$\bar{\varepsilon}_c = \frac{1}{\int_0^d w(s)ds} \int_0^d w(s)\varepsilon_c(s)ds \qquad (8)$$

prior to calculating current value of objective function (6). In the foregoing equations, g_i stands for component of tangential vector, *d* is the averaging length, *w* represents assumed weighting function, while *s* is the (spatial) distance along the fiber path, expressed here in the measurement point of a local coordinate system. The weighting function and averaging distance depend on the actual shape of the pump pulse (and pre-pump pulse in the *Neubrescope* system) used and spatial resolution, respectively, and should be appropriately adjusted.

Many different gradient and non-gradient based methods might be implemented to minimize objective function (6). In this study, the gradient method was employed, due to the higher convergence rate (total computational costs in a considered problem is high), the pipe thinning effect is local, and the large number of measurements data allows one to easily select a start point (initial guess). The gradient-based minimization methods require evaluation of the response sensitivity, z_i, with respect to unknown parameters (here thinning shape parameters), a_i:

$$z_i = \frac{\partial \varepsilon(a)}{\partial a_i} \tag{9}$$

The finite difference approach or direct implicit differentiation (e.g. [5]) can be used to obtain these values. The accuracy of the former is lower, while its computational cost is usually much higher, however, simpler to perform. Moreover, any commercially available codes can be employed.

In the present study, the minimization was performed using the trust region, Levenberg-Marquardt procedures, due to their self-regularization properties and stability. The sensitivities are obtained by means of automatic differentiation tools (utilizing the finite difference approach). The *Boundary Element Method* was used as a method of choice for calculating a model response (solving structural problem). Advantages of BEM over *Finite Element Method* in that particular application include the more accurate boundary strains evaluation, avoidance of domain discretization and, most of all, mesh distortion problems at the process of surface update and re-meshing. Furthermore, at each iteration of the solution process, only a small number of boundary elements, and thus the BEM matrices is modified, allowing one to use efficient update scheme and entirely avoid unnecessary reintegration. The efficiency, stability, and accuracy of this approach are demonstrated considering the test case presented in the following Section.

TEST CASE

In this example, the detection of thinning in the *polymethyl methacrylate* (PMMA) pipe sample (Figure 1 – left) is presented. The geometrical configuration of the pipe and location of optical fiber are shown in Figure 1 (right). The (non-thinned) thickness of the pipe was 10 mm. As thermophysical properties, the following values were assumed: modulus of elasticity 3.3 GPa, and Poisson's ratio 0.35. The applied internal pressure was monitored and was as high as 1.0 MPa. During the test carried out at Neubrex Co., Ltd., for validation purposes strain was also measured by means of four strain gauges.

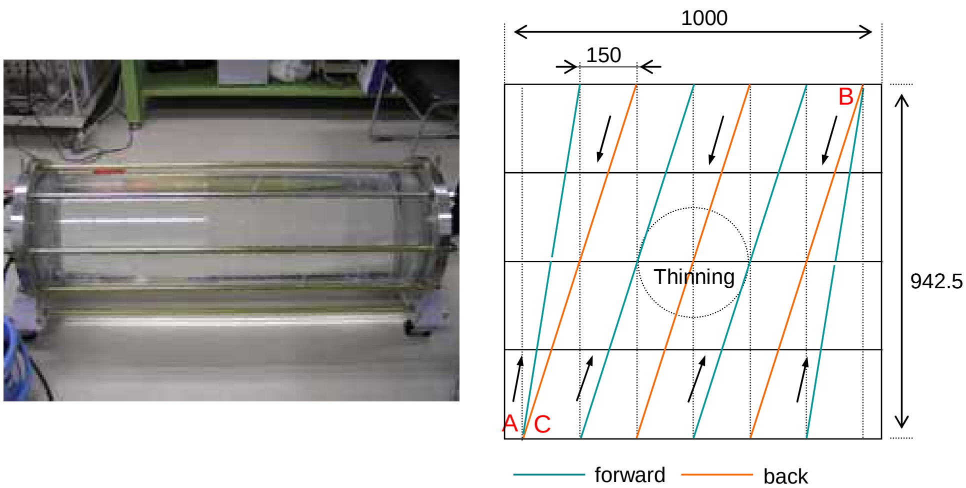

Figure 1. Experimental stand (left), dimensions with fiber path in unfolded view (right)

The structural mesh comprised 2,112 surface quadrilateral elements. The BEM formulation employed the nearly singular integration procedures [6], which were required due to small relative thickness of the analyzed domain, especially in the expected thinned area. It was assumed that thinning was circular-shaped and can be described using four unknown parameters, namely: size, depth and position in both circumferential and axial directions of the thinning. The results of estimation using measurement data gave a good agreement with available UT scan of thinning area [4].

In order to validate the inverse analysis algorithms and software, and additionally determine the maximum allowable measurements error level (in industrial applications being always much higher than in the laboratory-controlled environment), numerical experiments were also performed. In the numerical tests, the measurements strain in the fiber were simulated from the noise-free values (Figure 2, σ = 0.0), by applying the random errors of Gaussian distribution. This type of errors distribution in *Neubrescope* sensing system was confirmed in numerous experiments (see also Section 2). Several levels of measurement noises were imposed. Applied noise (above σ = 15.0 especially), made inverse solution procedure challenging. The selected data for levels σ = 15.0 and σ = 25.0 $\mu\varepsilon$ are presented in Figure 2.

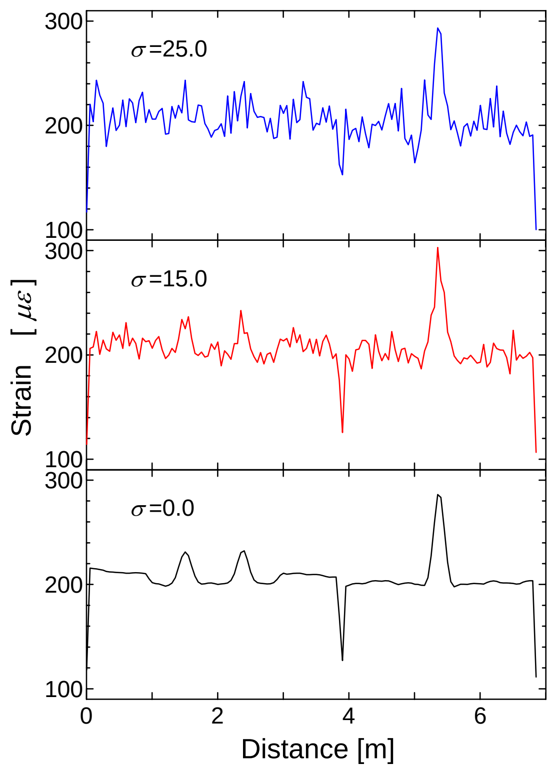

Figure 2. Simulated data with different measurement error levels.

For each analyzed noise level, up to 5 different data cases (problems) were generated. Moreover, in order to verify convergence of the implemented solution algorithm, different starting points (initial guess) of values were used. The convergence rate was high, and prescribed stopping criteria (tolerance in parameters and objective function change) were usually achieved in just a few iterations. An example convergence plot is shown in Figure 3.

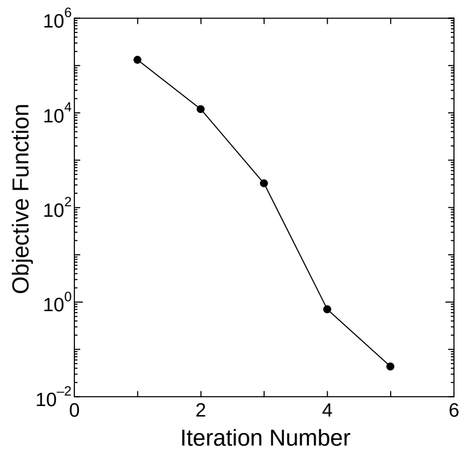

Figure 3. Objective function decrease versus number of iterations

Table 3. Estimation results – measurement uncertainty ± 15.0 με

Case ID	Estimated thinning				Objective function	Iterations
	radius	depth	hoop	axial		
1	152.889	4.914	3.151	0.494	8.208	8
2	143.330	5.395	3.122	0.497	8.516	10
3	145.375	5.146	3.140	0.504	8.622	8
4	146.183	5.081	3.133	0.494	8.310	8
5	157.038	4.832	3.206	0.494	9.165	9

Table 4. Estimation results – measurement uncertainty ± 25.0 με

Case ID	Estimated thinning				Objective function	Iterations
	radius	depth	hoop	axial		
1	135.983	5.472	3.140	0.505	14.221	12
2	142.627	5.066	3.142	0.520	13.464	7
3	143.416	5.247	3.121	0.493	13.285	10
4	146.816	4.684	3.121	0.499	13.822	8
5	146.538	4.656	2.914	0.496	13.426	7

Tables 3 and 4 list the obtained solution results for noise levels as high as $\sigma = 15.0$ (typical for *Neubrescope* sensing system) and $\sigma = 25.0$ με. The target values in both cases were: 150, 5, 3.14, and 0.5, for radius, depth, and location in hoop and axial directions, respectively. The inverse procedure converged with reasonable accuracy even in the test-runs for extreme, in this particular problem, measurement noise level of $\sigma = 35.0$ με (twice the errors of *Neubrescope* system). In all analyzed examples, the algorithm proved to provide reliable, stable, and accurate calculation results.

CONCLUSIONS

In this paper, we presented a robust thinning detection method, built upon the *Neubrescope* sensing system. The *Neubrescope* system provided highly accurate, of cm-order spatial resolution measurement data. We examined in detail the accuracy and uncertainty of the data, taking into account influence of polarization average, frequency-scanning step, as well as self-calibration. The strain values in the fiber are used to detect shape, location, and depth of pipe thinning. The algorithm implements the *Boundary Element Method*, sensitivity analysis, and full 3D structural model. All required numerical enhancements, advantages, and drawbacks of this approach are also presented. The results of series of tests are included, demonstrating the high accuracy and reliability of the sensing system, as well as the stability, and robustness of the numerical algorithms.

The sensing system presented in this paper has been successfully implemented in a commercial, industrial application, running already for nearly a year. In this particular application, the portion of the measurements data (straight portions of pipeline) were used to determine the loading and supporting conditions, while remaining data employed for evaluating the thickness in the area of interest (elbows). The accuracy and, most of all, spatial resolution of the Neubrescope strain measurements were the key components allowing us to detect corrosion-based thinning with reasonable accuracy.

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