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Distributed Fibre Optic Acoustic and Vibration Sensors for Industrial Monitoring Applications

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Abstract:
We investigate the usability of distributed fibre optic acoustic sensing (DAS) for innovative and advanced monitoring applications in industrial and civil infrastructure installations. In this paper, we report on our ongoing application-oriented research activities regarding the utilization of DAS based on coherent optical time-domain reflectometry (C-OTDR) for condition monitoring of a variety of infrastructures. Specifically, our research presented here aims at acoustic condition monitoring of and fault detection in pipelines and industrial piping systems, at acoustic condition monitoring of rollers in industrial conveyor belt installations, and at acoustic condition monitoring of and threat detection in extensive submarine power cables, respectively. Furthermore, we show a method to mitigate the effect of sensitivity fading of C-OTDR based DAS due to unstable environmental conditions via the modification of the sensor fibre. This can help to provide a continuous adequate sensor functionality for a number of different industrial monitoring applications.

Key words: distributed acoustic sensing, DAS, distributed fibre optic sensors, C-OTDR, condition monitoring

Introduction

Condition monitoring of industrial or civil infrastructures is imperative to avoid failures of critical installations. Having current condition information at hand also helps minimising off times since maintenance can be planned more long term. The implementation of certain conventional monitoring approaches is often made difficult by hazardous environmental conditions or the lack of access. In addition, the use of point sensors is often insufficient for the monitoring of extended structures, as gaps in sensor coverage are unavoidable. Distributed fibre optic sensors provide the possibility for spatially continuous monitoring and can be used in certain hazardous environments, e. g. high voltage, where other conventional sensors can not be used. In particular DAS, being a dynamic sensing method, opens up the possibility to detect and localize disturbances or other sudden events as well as to capture acoustic or vibration patterns caused by the operating conditions. Therefore, DAS is a perfect candidate for real-time monitoring of industrial processes or condition monitoring of fixed installations. Even though it is a relatively new concept, DAS is already employed in a number of fields, ranging from geophysical applications and borehole monitoring in the oil and gas industry to pipeline and general perimeter security applications. Distributed acoustic and vibration sensing is, however, just emerging as a considered approach for condition monitoring purposes.

The division Fibre Optic Sensors of BAM is currently investigating new and innovative uses of fibre optic DAS for condition monitoring applications in a variety of industrial and civil infrastructures. Each type of infrastructure holds in store a specific set of challenges related to the use of fibre optic DAS based on C-OTDR [1,2] for condition monitoring. These issues cover a broad range: from questions regarding the effect of sensor application characteristics on sensitivity; on how to achieve the long sensor range for very large structures to be monitored or related to sufficient spatial resolution and how to avoid sensing gaps, thus enabling more precise localization of mechanical disturbances, especially when dealing with sensitivity fading [3]. Therefore, our application-specific research thus also gives us the opportunity to investigate the characteristics of DAS on a more fundamental level.

Here, we present our ongoing application-oriented research efforts targeting the use of DAS specifically for condition monitoring of industrial pipelines and piping systems [4], of rollers in industrial heavy-duty conveyor belt systems [5], and of submarine power cables, respectively. Further applications for DAS-

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based condition monitoring currently being investigated by our division also include structural health monitoring of bridges [6]. Furthermore, we present a method to enhance sensitivity by mitigating the effect of sensitivity fading via local modification of the sensing fibre.

Our distributed acoustic and vibration sensing approach is based on single-pulse direct-detection coherent optical time domain reflectometry (C-OTDR) [1,2], which measures local variations in Rayleigh backscatter intensity in optical fibres due to dynamic strain changes along the fibre axis caused by external acoustic disturbances or vibration patterns. During the experiments described here, we utilised a commercially available C-OTDR DAS device (Helios HSI DAS from Fotech Solutions Ltd.) with a spatial sampling of 0.68 m and a range of possible pulse widths between 10 and 1000 ns. An increased pulse width leads to enhanced sensitivity and an extended range of adequate sensor performance, but will also result in a decreased spatial accuracy as information is “smeared" along a length of fibre corresponding to half of the interrogator pulse width. Thus, the possible interrogator pulse widths correspond to spatial accuracies between 1 and 100 m.

Acoustic Condition Monitoring of Pipelines

Distributed fibre optic sensors have been employed for monitoring of pipeline infrastructure for some time. It is expected that useful information about the pipe's condition could be ascertained by utilising a sufficiently sensitive DAS system with the sensors being applied onto the pipeline's surface. This would offer the possibility to early detect arising damages to the pipe, e.g., leaks or the formation of cracks, as well as changes in internal conditions like corrosion, sedimentation or blockages via the measurement of changes in the pipe’s acoustics. In the framework of the BAM research project “AGIFAMOR", we are investigating the utilisation of C-OTDR based DAS with that specific aim [4].

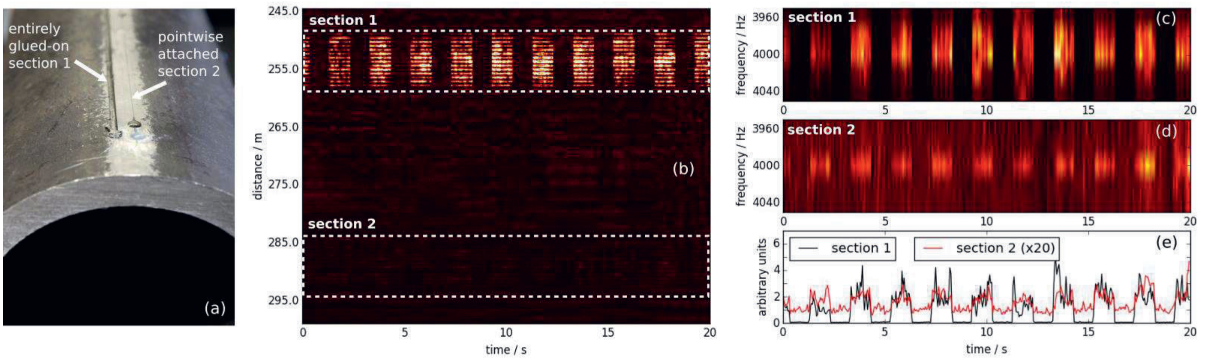

Fig.1. (a) Steel pipe with two differently applied sensor fibre segments, (b) C-OTDR signal intensity in 80 Hz frequency band around center frequency of 4 kHz plotted over fibre length and recording time when applying a 4 kHz signal in subsequent 1 s bursts to the pipe. (c),(d) Signal intensity averaged over a range of 10 m for each respective sensor section versus frequency and time. (e) Comparison of peak intensities at 4 kHz from (c) and (d), the intensity in section 2 was scaled by a factor of 20.

Our investigations focus on the measurement of acoustic signals transmitted through the pipe wall. These signals are expected to carry information about the external as well as the internal condition of the pipe. Therefore, as an experimental starting point, we applied artificial acoustic signals of various frequencies to a pipe's surface and tested the performance of our DAS system using standard single mode optical fibre as sensor. Our motivation here was to study the effect of the type of sensor application on the quality of the measurement data. To that end, we glued two segments of the same optical fibre to the surface of a 1 m stainless steel pipe using epoxy-resin adhesive. One section was glued to the pipe's surface along the entire length of the pipe (section 1), the other was attached only in certain equally-spaced positions (section 2). Both were separated by an additional 30 m of fibre to exclude the possibility of one section influencing the other when using long interrogator pulses.

Fig. 1(a) shows a photo of the two application types. The excitation signals were generated by a piezo-speaker attached to the pipe's surface. Fig. 1(b) shows the intensity of the measured C-OTDR signal in a narrow spectral band around 4 kHz for an applied 4 kHz signal of consecutive 1 s bursts versus the fibre length and time. In the plot region corresponding to section 1 the applied signal is clearly visible in a range of approximately 10 m. This is due to the large pulse width of 100 ns of the C-OTDR system resulting in a reduced spatial accuracy of 10 m. In the pointwise attached sensor section 2 the applied signal is barely visible.

Figs. 1(c) and (d) depict time-dependent signal intensities around the applied frequency of 4 kHz after averaging over a range of 10 m corresponding to each sensor section. It is quite obvious that the continuous application results in significantly improved sensitivity properties than the sparse (pointwise) application, which is due to better signal transduction. In Fig. 1(e) the peak intensities at 4 kHz for both sections are plotted over time. It can be seen that sensor section 1 yields a measured signal intensity approximately 20 times higher than the sparsely applied section 2.

Nonetheless, gluing large lengths of sensor fibre continuously along entire pipeline systems is impractical. Furthermore, the spatial accuracy of the sensor needs to be improved despite the long interrogator pulses necessary for sensor functionality to cover large lengths of pipeline. A helical sensor application, achieved by evenly winding the fibre around the pipe could be a viable solution. Our experiments in that direction so far show that a comparable sensitivity can be achieved without the need for gluing if the fibre is wound tightly enough (results not shown). This method also provides us with enough spatial sampling points to compensate for the unavoidable sensitivity fading via post-processing of the measured data.

In the next steps we will investigate the feasibility of detecting the formation of cracks in the pipe walls and of measuring flow noises while optimising the acoustic signal transduction to the sensor.

Acoustic Condition Monitoring of Industrial Rollers

Industrial heavy-duty conveyor belt systems for material transport can be extensive structures with a large number of rollers, which are prone to wear out damage.

Real-time distributed fibre optic condition monitoring of these systems can reduce the threat of unplanned shutdowns due to sudden roller failure since damages can be recognised in time so that appropriate maintenance measures can be implemented. For our research regarding the utilisation of C-OTDR based DAS for this condition monitoring application, we investigated three different representative rollers in an acoustic test stand [5]. One was practically factory-new, while the other two had been retracted from active use due to damage diagnosed by auditory inspection. The test stand was acoustically isolated from external noise. The respective roller under investigation was mounted in the test stand and driven by a conveyor belt which was pressed against its surface. To measure the roller's acoustic emission, we connected the fibres in a standard telecommunication cable as sensor to our DAS system. The cable was placed in several passes around the test stand and was in direct physical contact with the shaft of the roller in one point. Fig. 2 shows a photo of one of the rollers in the test stand with the segment of the sensor cable closest to the roller visible in the foreground.

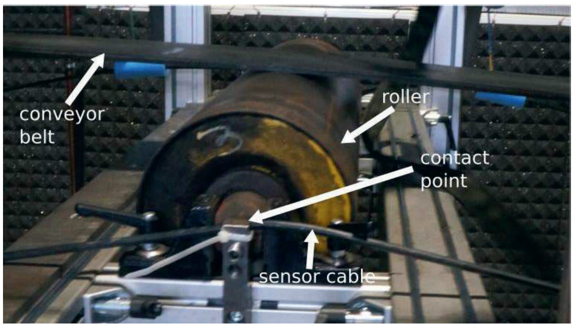

Fig. 2. Photo of one of the examined industrial rollers with the conveyor belt in the acoustic test stand. The fibre optic sensor cable used for C-OTDR measurements can be seen in the foreground.

Each roller was driven with several typical belt velocities and the acoustic emission was measurement by our DAS system using various different pulse widths to identify the optimally balanced working point with respect to spatial resolution and sensitivity.

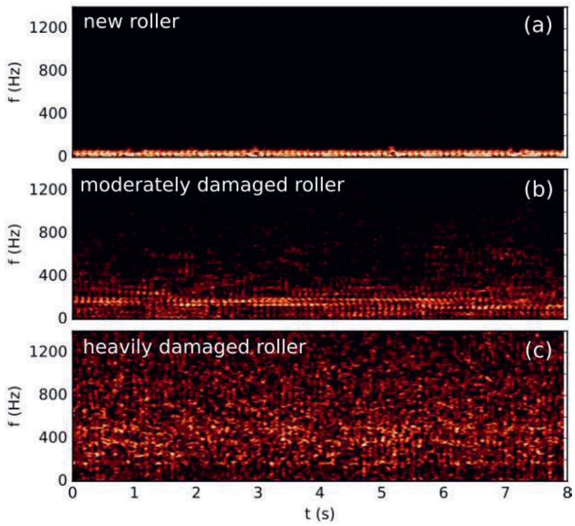

Fig. 3. Spectrograms calculated from C-OTDR traces measured in the sensor range bin closest to the contact point for the three investigated rollers showing their respective acoustic signatures. (a) New roller, (b) moderately damaged roller, (c) heavily damaged roller.

Fig. 3 depicts exemplary time-dependent acoustic spectra calculated via Short Time Fourier Transform from the C-OTDR traces measured in the sensor range bin corresponding to the point of contact for the three different rollers. (a) depicts the time-dependent spectra of the new roller, (b) is a spectrogram for a moderately damaged roller and (c) for a heavily damaged one. The differences in spectral characteristics are quite apparent: the new roller has a narrow acoustic emission spectrum, the moderately damaged one exhibits a broader spectral characteristic and the vibrations of the heavily damaged roller shows yet an even broader spectral composition. It is therefore appreciable that the spectral width of the vibrations of the roller can serve as an indicator of the condition of the device. Future investigations should test our lab results in real-life conditions.

It should be noted, however, that the significant background noises in an operating conveyor belt system caused by its load could limit the applicability of this approach. The identification of more precise condition-specific spectral features in the acoustic emission of rollers is necessary to distinguish the conditions of different rollers in operation and shall be included in future studies involving these rollers.

Acoustic and Vibrational Condition Monitoring of Submarine Power Cables

Acoustic condition monitoring of submarine power cables can help to avert failures and damages due to external influences like nearby anchor drops, trawler fishing or construction, which are the most common causes for damage to or destruction of underwater power cables. These events result in acoustic signals or vibrations in the seabed, the early detection and localisation of which is necessary to have sufficient time to react to the threat.

In the framework of the national research project "Monalisa", our division is investigating the implementation of C-OTDR DAS for condition monitoring of power cables leading to offshore wind parks. Usual distances from the shore of these installations result in a desired target sensor range of up to 100 km. The biggest challenge is thus to achieve adequate sensitivity over the entire length of power cable and still have the capability to localise a disturbance with a spatial accuracy of 10 m or less.

Many commonly employed power cable designs already include embedded optical fibres meant for communication purposes. In a first step experiment, we tested the usability of this kind of fibre for distributed acoustic sensing. To that end, we connected the fibre in a 6m specimen of a common medium voltage power cable to our C-OTDR device. The fibre in the cable was encapsulated in a gel-buffered metal loose tube, the gel usually serving as strain relief. The metal capillary was embedded in the outer shielding layer of the cable, made out of copper wires, directly below the outer polyethylene (PE) mantle of the cable. The cable specimen is depicted in Fig. 4. Considering that acoustic stimuli have to pass through several layers of different media to reach the sensor fibre, a significant dampening of external excitations can be expected.

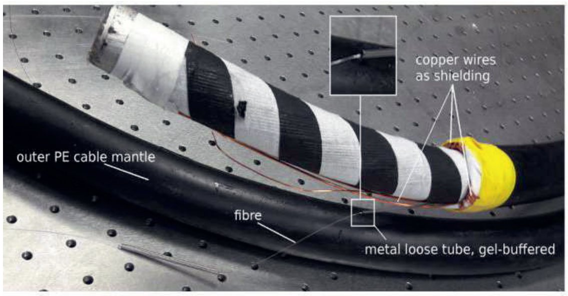

Fig. 4. Photo of examined power cable specimen with embedded single mode optical fibre.

In the course of the experiment, the cable specimen was excited by slightly tapping it in different positions to test whether such a low-intensity stimulation would be sufficient to register in the recorded C-OTDR traces. We used different pulse widths, with our sensor system showing a clear response to the induced vibrations for pulse widths as low as 20 ns. Fig. 5 shows the resulting backscatter timeseries (a,b) as measured in a single sensor range bin with the DC offset removed (black lines) and the corresponding calculated spectrograms (c,d) for that pulse width.

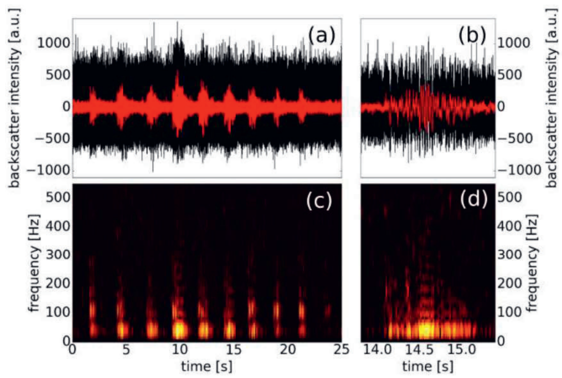

Fig. 5. Vibrations in the power cable induced by light tapping as measured by C-OTDR using the embedded fibre as sensor. (a) C-OTDR trace measured in a single sensor range bin (black line, DC removed), (b) magnified view showing the vibrations resulting from a single excitation, (c) and (d) time-dependent spectra corresponding to the dynamics shown in (a) and (b), respectively. The red lines in (a) and (b) show the C-OTDR traces after applying a lowpass filter for better visibility.

Fig. 5 (b) and (d) show a magnified view of a single vibration in the time (b) and frequency (d) domain, respectively. The red lines depict the backscatter traces after lowpass filtering with a cutoff frequency of 500 Hz.

Particularly in the frequency domain the vibrations are clearly distinguishable. This outcome, that even with short interrogator pulses, also meaning a reduced sensitivity of the DAS system, a low-amplitude impact-like excitation could be detected is very promising for further investigations. The short pulse width effectively emulates the significantly reduced probe pulse intensity of much longer C-OTDR pulses after being attenuated along large lengths of optical fibre in actual large-scale cable installations. We expect a significant boost in sensor performance after implementing a power cable-specific sensor design and embedding.

Next steps will also include comparing the performance of different types of embedding and application of the sensor fibre for long-range detection of impact-induced vibrations.

Enhancing DAS sensitivity for application in temperature unstable environments

Reliability is the key parameter with real-time condition monitoring of industrial infrastructure when utilising distributed fibre optic acoustic sensing. Due to the nature of C-OTDR based DAS, the sensitivity of the measurement system does not stay constant over time [3]. This is especially the case if the temperature drifts or changes rapidly. Depending on the application and environmental conditions, this behaviour could result in temporary low local sensitivity or even its total loss.

We show a possibility to reduce this problem of sensitivity fading via the use of optical fibre with two regions with increased backscattering. For that purpose, we modified a fibre specimen by locally boosting the backscatter amplitude by UV-laser inscription to overwrite the random strain transfer function with an "effective" interferometer length. The separation between these regions was set to be ~2 m. The backscatter amplitude along the modified fibre segment as measured by a commercial Luna OBR is shown in Fig. 6.

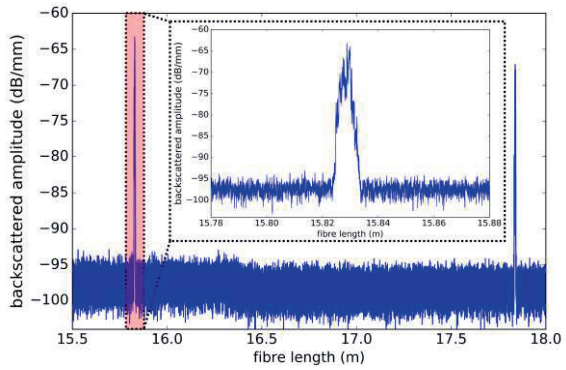

Fig. 6. Backscattering profile of the modified FUT as measured with a commercial Luna OBR system.

To validate the performance difference between a standard ("plain") and a manipulated ("scatterer") fibre segment, we performed dynamic strain measurements using a piezo element driven by a function generator. To that end, both FUT were attached to and then simultaneously strained by the piezo during the measurement interval. The frequency of excitation was set to be 100 Hz with a homogeneous voltage amplitude of 200 mV. The corresponding peak dynamic elongation was approximately 50 nm. During the measurement, the environmental temperature was forced to fluctuate in a 2°C temperature range to evoke enhanced sensitivity fluctuations and thus fading.

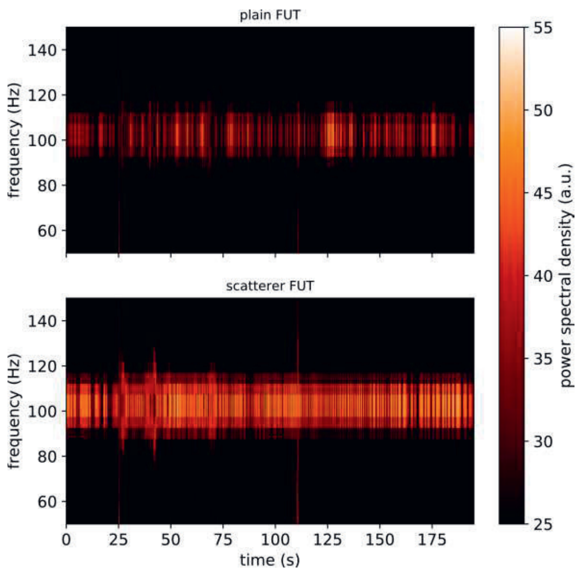

Fig. 7. Resulting short-time Fourier transform in the band between 50 Hz and 150 Hz for both fibres under test and an excitation signal frequency of 100 Hz.

We used our commercial C-ODTR system to probe the dynamic fibre elongation. A short-time Fourier transform of the backscatter amplitude over time along the fibre was performed to visualise the effect of sensitivity fading (see Fig. 7). It can be clearly observed that the power spectral density (PSD) for both FUT fluctuates over time, as was expected as a result of the unstable environment temperature. Keeping in mind that the dynamic strain amplitude stays constant over the whole measurement interval, this means that the instantaneous sensitivity is affected by the temperature drift. When comparing both FUT, it

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can be observed that the modified "scatterer" FUT shows a higher mean PSD. This implies a higher mean sensitivity as well. In addition, the "scatterer" FUT shows fewer time intervals without significant PSD, i.e., fewer time intervals with a complete loss of sensitivity.

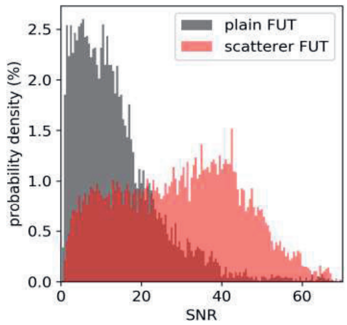

Fig. 8. Distribution of the calculated SNR for both compared fibres under test.

In an actual application, the detection of this 100 Hz excitation would be possible if the PSD is higher than three times the standard deviation (3σ) of the PSD of the noise floor, which we thusly define as signal to noise ratio. Fig. 8 shows the distributions of the SNR for both respective FUT. The plain fibre FUT's distribution has a maximum at a lower SNR, in contrast to the more flat SNR distribution of the scatterer FUT. The advantage of modifying the fibre by inscribing the two enhanced scattering regions becomes especially clear when comparing the mean SNR for the "plain" FUT with the one for the modified "scatterer" FUT, which are 15 and 24.7, respectively. This local boost of sensitivity and subsequent reduction of fading could be extended to the entire sensing fibre. Therefore, we propose to use this technique especially for fibre optic acoustic sensors used for industrial monitoring applications in temperature-unstable environments.

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