DISTRIBUTED OPTICAL FIBRE ACOUSTIC SENSORS – FUTURE APPLICATIONS IN AUDIO AND ACOUSTICS ENGINEERING.

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1 INTRODUCTION

First successful experiments with optical fibre acoustic sensors were performed in 1970s by Bucaro et al.[1] and Cole et al.[2]. Those and later developments were primarily concerned with point sensors which are equivalent to single microphone or a microphone array with fixed number of microphone. Optical fibre acoustic sensors utilise pressure induced variations in the refractive index of the fibre and its geometrical deformation caused by flexural wave to measure acoustic disturbance[3].

Single point optical fibre acoustic sensors are usually more expensive than microphones. However, if a large number of sensors is needed, distributed optical fibre sensors can offer a cost-effective alternative to microphone array due to the possibility of mapping the sound pressure level as a function of distance. Historically the oldest application of distributed optical fibre sensors (DOFS) were to measure the integrity of optical fibres along long telecom optical links. Just recently the focus has shifted towards distributed measurements of sound and vibration[4].

This paper briefly reviews the optical fibre distributed acoustic sensor technology. First, we look into distributed sensing principles in more details and compare different methods. In the next section, we will discuss the principle of Phase Optical Time Domain Reflectometry (φ-OTDR) and Rayleigh backscattering, which is used in the system designed and built by Masoudi et al.[5]. We will discuss the limitations of the system from acoustics point of view. Then, we propose possible applications of such a system in acoustic measurements. In sections 4–6, the results of the preliminary experiment performed in a reverberation chamber are presented and discussed.

2 DISTRIBUTED SENSING TECHNIQUES

2.1 Scattering of light in optical fibre

At this point one needs to explain the mechanism of light scattering in optical fibre. When light pulse is travelling through fibre, light scatters in all directions. In DOFS we are interested in backscattered light i.e. the part of the scattered light which travels back, towards front-end of the fibre. We are interested mainly in Brillouin and Rayleigh scattering as those phenomena allow the detection of dynamic strains induced by acoustic pressure.

The intensity of Brillouin scattering depends on strain and temperature. In addition, the frequency of the Brillouin backscattered light is also dependant on temperature and strain. Brillouin scattering is the result of the interaction between the incident light and the acoustic phonons in the fibre. Acoustic phonons are vibrational modes of atoms and they are generated by thermal processes. Although Brillouin scattering DOFS are capable of measuring absolute strain, but unlike Rayleigh scattering DOFS, they have low backscattered intensity compared with Rayleigh scattering and therefore they require large number of averaging. This limits the application of Brillouin scattering to slow-varying strain and temperature measurements[4].

Rayleigh scattering DOFS offer approximately 18dB higher backscattered signal level and are successfully employed in commercial DOFS systems. They are also used in the DOFS system developed by Masoudi and Newson[5,6]. Rayleigh scattering occurs due to random refractive index fluctuations in an otherwise homogeneous medium[7,4]. During the optical fibre manufacturing process inhomogeneities are formed, which cause random density fluctuations along the fibre. Movement of these inhomogeneities due to strain of the fibre cause a change in the phase, intensity and polarization of the Rayleigh backscattered light.

2.2 Optical time domain reflectometry

In practical systems Rayleigh scattering is employed in a fibre interrogation technique which is called Optical Time Domain Reflectometry (OTDR). There are three variants of the technique: Phase–OTDR (φ–OTDR), correlation–OTDR and polarization–OTDR. Only φ–OTDR will be discussed here as it is the only one capable of quantifying disturbance[4]. In φ–OTDR technique, the phase difference between the Rayleigh backscattered light from two scattering centres is proportional to the distance between them[4]. Therefore, a φ-OTDR system is capable of detecting longitudinal strain of the fibre induced by acoustic pressure.

2.3 Limitation of the technique and specific limitations of the current system

Optical fibre sensors have low sensitivity in air because of mechanical impedance mismatch. Therefore, they have been used primarily as hydrophones. For audio frequency acoustic signals, to be able to detect sound pressure, Masoudi et al. [5] used polystyrene sheet and Wu et al.[8] metal sheet. Those ad-hoc arrangements are not practical and formally analysed. To improve sensitivity of optical fibre sensor, the use of appropriate coating material could be investigated. Possibly a composite which would facilitate energy transfer from air to the fibre core. Hocker[3] has shown that using composite structures will indeed increase stress in the fibre, therefore improve the sensitivity by a factor of 10 to 100. Hocker's experiments were performed in water which means sensitivity was higher than in the air even for the bare fibre due to better impedance match. This suggests that one can expect considerable difficulties with achieving sensitive and linear transducer for use in air.

As far as linearity is concerned, the Rayleigh scattering process is very nonlinear. It is possible to linearize the response by differentiation over a section of the fibre[9]. In the current setup[6] first proposed by Posey et al.[7] this is done by detecting phase difference of backscattered light from two sections of the fibre using an interferometer[9].

Using the intensity of Rayleigh scattering, it is not possible to measure absolute value of strain[4]. Phase-OTDR can only detect relative strain between two points in the fibre[6], so calibration might be required to obtain an absolute value, perhaps using Brillouin scattering. For relatively short or geometrically constrained fibre arrangements, a calibration regime could be developed if the properties of acoustic source (strength, directivity) and sound field (i.e. anechoic chamber) are known.

To resolve acoustic field spatially and avoid spatial aliasing, the microphone spacing in the microphone array should be less than half of a wavelength for the highest frequency signal to be measured, according to the spatial equivalent of Nyquist theorem. This means that for 20kHz in air the spacing should be less than 0.85cm. This can be difficult to achieve in practice using standard microphones. Distributed sensor in principle could be a solution for this problem. Unfortunately, most systems including the one developed by Masoudi et al.[5,6] have spatial resolution of 1m. This is due to the pulse width which determines the length of the scattering regions and the interferometer path imbalance, which determines gauge length[7]. Normally, the pulse width is dictated by a trade-off between the spatial resolution and the range, which, for conventional applications along the pipeline, is measured in kilometres rather than metres. Thus, in the case of acoustic measurements it could be feasible to use shorter pulses as the range is shorter. Shorter pulse decreases the signal-to-noise (SNR) ratio as the energy introduced to the fibre is smaller. This can be improved by increasing the number of averages or signal processing[10]. Alternatively, due to small diameter of the fibre, one can conceive suitable geometrical arrangements to effectively improve the spatial resolution by, for example, coiling the fibre and applying appropriate signal processing techniques to unwrap the response. Limited spatial resolution affects high frequency limit of the system due to spatial Nyquist theorem mentioned above. 1m resolution means that sound field can be resolved unambiguously up to approximately 170Hz.

Some sort of mechanical support would need to be employed, as the fibre itself is difficult to handle because of its small diameter. Possible solutions could involve applying some coating to bare fibre which would improve its acoustic sensitivity and mechanical handling or rigid frame for array arrangement, which apart from improving sensitivity and resolution would provide repeatable setup.

3 CURRENT DEVELEOPMENTS AND POSSIBLE APPLICATIONS IN AUDIO AND ACOUSTICS

In recent years we can see rise in research in distributed vibration and acoustics sensing using optical fibre, especially Phase-OTDR using Rayleigh The most common application of the DAS is in oil in gas industry to detect leaks in pipes. One can however conceive other applications, which could be useful for advanced acoustics measurements. There are some shy attempts to use the sensor to measure audible sound[5,8]. However their parameters such as sensitivity, spatial resolution, signal-to-noise ratio are nowhere near the quality needed for advanced acoustic measurements.

The measurement techniques in acoustics which require or could be improved by using large number of microphones include:

- Beamforming
- Nearfield acoustical holography
- Directivity measurement of loudspeakers
- Broadband intensity measurements (avoiding different microphone setup for different frequency ranges)
- Measuring the performance of sound field reproduction systems

Beamforming is used mainly in far field noise source identification mainly from distant sources such as aircrafts, train, factories etc. Nearfield acoustical holography (NAH), on the other hand, is used very close to the source and can visualise sound radiation from the structure. For directivity measurement one normally employs one of the following techniques: turntable and one microphone, moving microphone, or array of microphones. All of those techniques could benefit from using fibre optic s transducer since weight of the array can be reduced for NAH and Beamforming and for transducer directivity measurements the speed of setting up and angle resolution could be improved. In sound field reproduction, one is interested in measuring pressure profile of reproduced sound field.

4 EXPERIMENTAL SETUP

Masoudi et al.[5] have shown that the current system has very low sensitivity and bare fibre was unable to detect any sound. Therefore, the fibre was attached to a polystyrene sheet to improve its sensitivity.

To quantify the absolute capabilities of the measurement system, preliminary experiment was set up in a reverberation chamber. The choice of reverberation chamber as the test facility was based solely because of ease of generating large sound pressure levels. To test the sensitivity of DAS to sound pressure, a 4m long optical fibre was fixed between two clamps in the reverberation chamber as shown in figure 1. A large speaker was placed at the centre of the sensing fibre at the distance of 30cm and a B&K free-field microphone type 4190 with B&K preamplifier type 2669. The microphone is positioned off-centre 30cm from the fibre to monitor the sound pressure level (SPL) at the fibre. A 50m long fibre was used to connect the sensing unit to the 4m section under test while the other end of the 4m section was connected to 400m delay fibre. The delay fibre was placed inside the control room to isolate it from the perturbation in the reverberation chamber. A range of different frequencies and sound pressure levels were tested in the chamber. To measure the frequency range of the system, the SPL was set to 115dB and the frequency of the speaker was changed in 250Hz steps from 250Hz to 1750Hz.

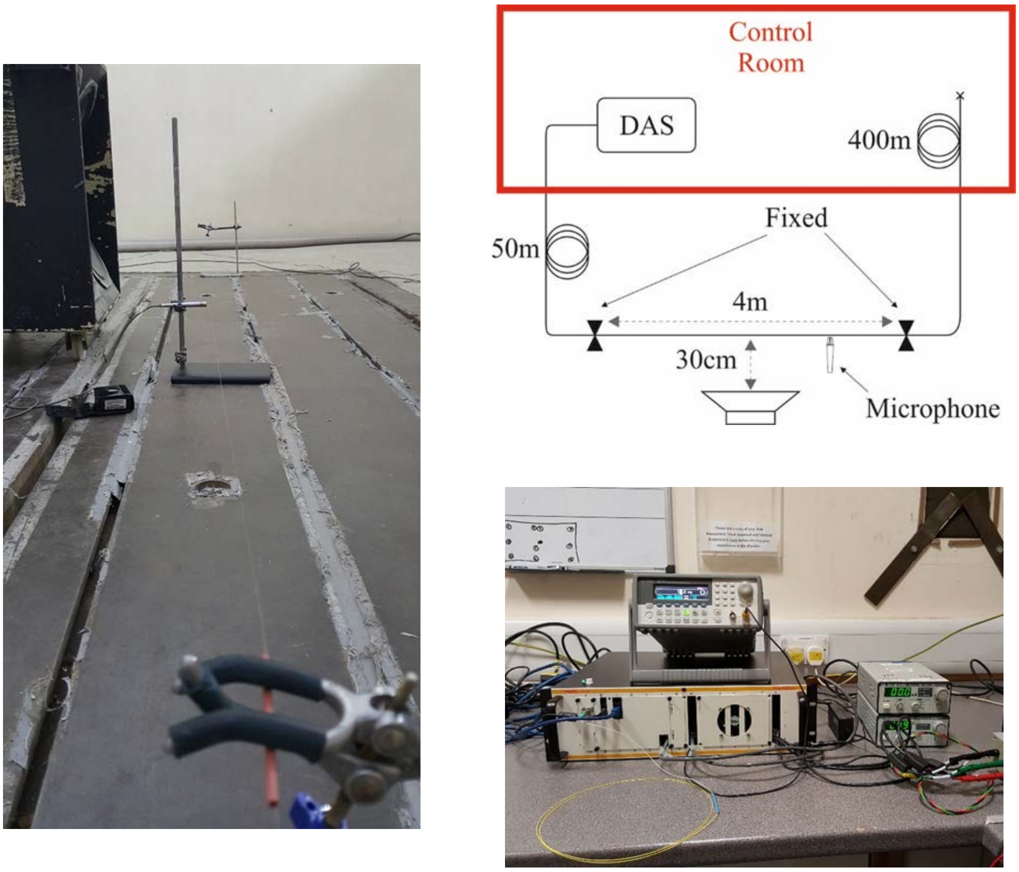


Figure 1. Experimental setup

5 RESULTS

Figure 2. Presents colour map plot for pressure induced strain at the fibre for 500Hz excitation at three different sound pressure levels i.e. 108,113 and 118 dB. The colour scale is fixed for all the plots so the difference in level can be easier to see. Figure 3. shows six colour maps for 115dB SPL excitation for different frequencies i.e. from 500Hz to 1750Hz in 250Hz steps. In this case, the colour scales are different for each plot to maximise visibility of the peaks. Figure 4. Shows spectrum of the multi-tone signal used in the last test and the fibre response.

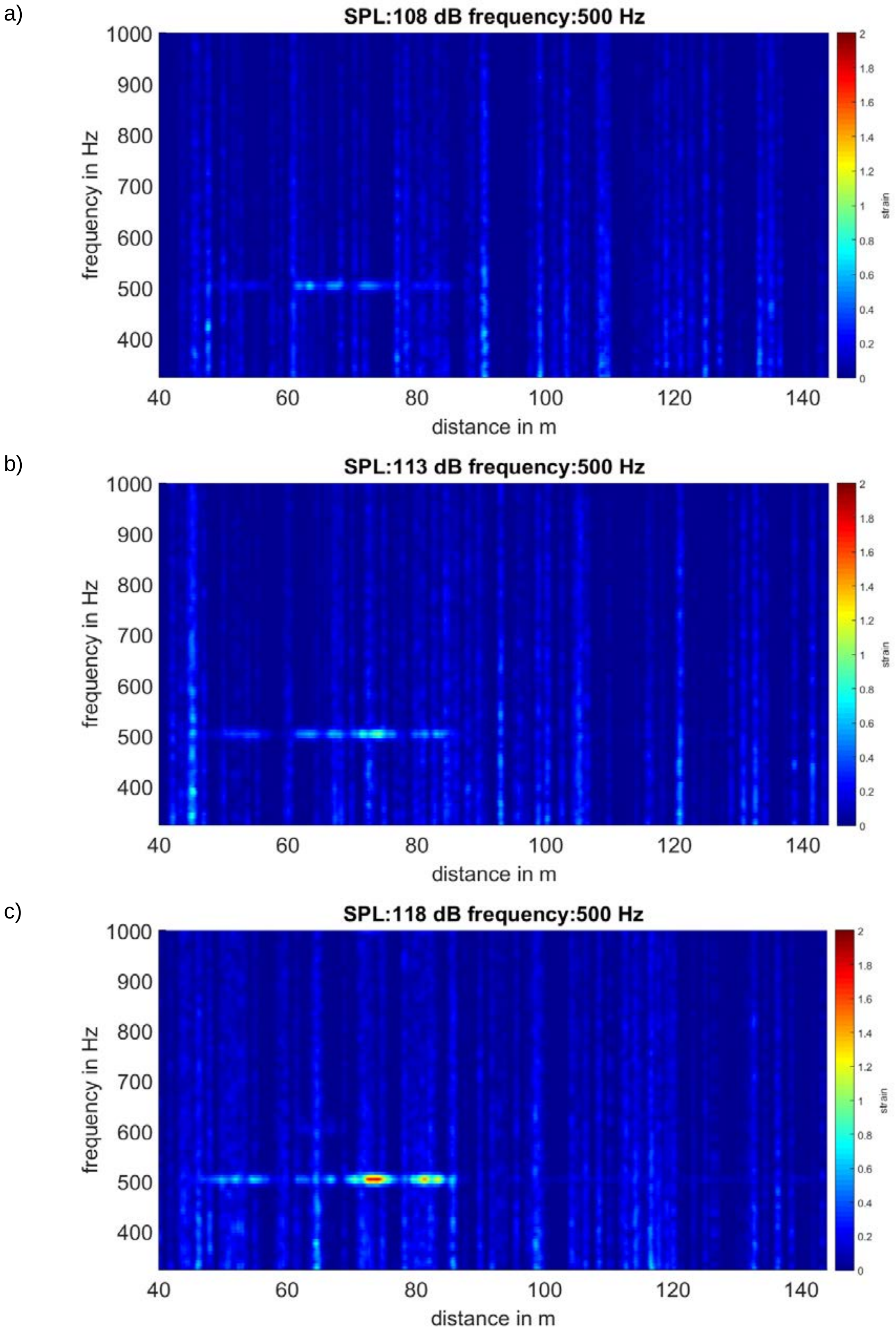


Figure 2. Measured pressure induced strain in the reverberation chamber for 500Hz excitation and different sound pressure levels a)108dB, b)113dB, c) 118dB

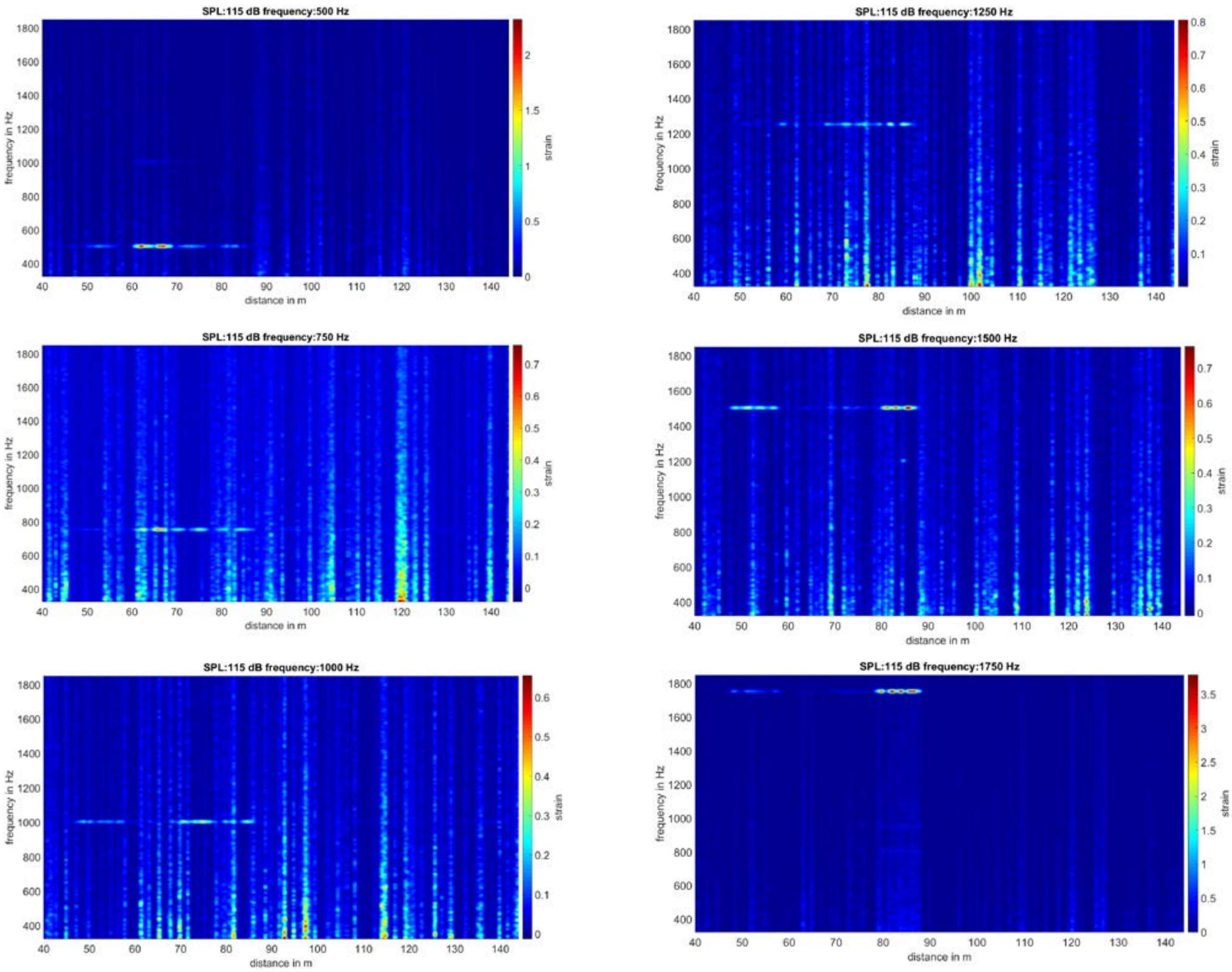


Figure 3. Measured pressure induced strain in the reverberation chamber for 115dB SPL for single tone excitations from 500 to 1750Hz with 250Hz step excitation, note that scale is not normalized and is different for each plot

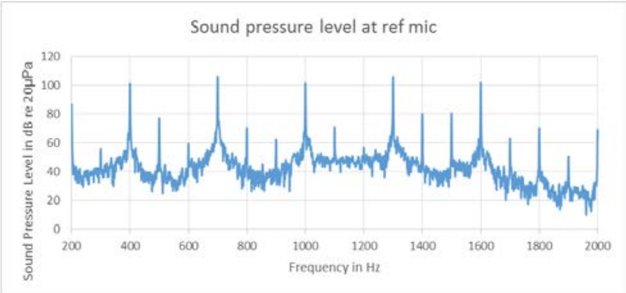
6 DISCUSSION

The data shows that the system with bare fibre used can detect narrowband signals as well as multi-tone signals at the levels which can be encountered in real life i.e. 108–115dBSPL Although the preliminary results from the reverberation chamber are promising, there are too many uncontrolled elements in the test which makes the interpretation of the data difficult. For instance, it is not clear whether the clamps were picking up the vibrations or the sensing fibre, or how the rest of the fibre picked up the signal. Also, due to long reverberation time, controlling the resonances in the chamber proved to be very difficult. Another complication is unknown pattern of the standing waves in the reverberation chamber and acoustic and vibration pickup outside the section of the fibre clamped. Also longer section of the fibre should be used.

Analysing figures 3 and 4 one can be confused since maximum of the signal appears in different places along the fibre. That can be various objects vibrating touching the fibre such as: walls, laboratory tables and equipment etc. having different vibrational responses to the acoustic excitation. This is a clue for the future experiments that not only clamped section should be taken into account, but the whole fibre section should be accurately described, so any spurious sources of vibration could be correctly identified and eliminated for example by isolating the fibre f. This also presents practical engineering consideration for practical use and implementation of the system. Both sets of results show high levels of broadband noise with peaks every 2m. That could be eliminated in the future when more sensitive fibre will be used and better signal processing will be employed.

Due to unknown standing wave pattern occurring in the reverberation chamber any frequency response was difficult to measure reliably. Also as mentioned earlier the system has 1m spatial resolution which means that the responses are integrated over the fibre section and any signal above 170Hz cannot be resolved accurately in spatial domain.

Figure 4 shows that the system is capable of detecting multi-tone signals.



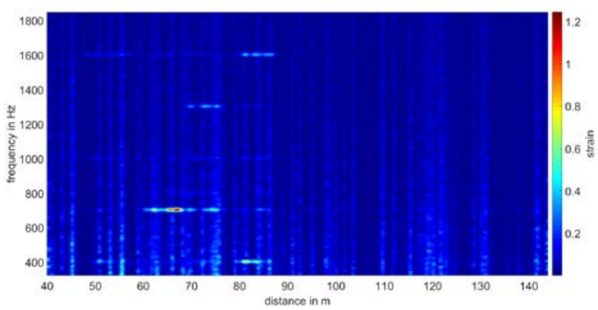


Figure 4. Multi-tone signal applied SPL at reference microphone 1cm from the fibre (left plot), strain colour map distance vs. frequency (right plot)

7 FUTURE RESEARCH

In the near future, the system will be tested in the anechoic chamber in order to have more controlled conditions. Using the anechoic chamber, the results will be easier to interpret as sound pressure distribution in free-field conditions could be predicted more accurately and complicated pattern of standing waves which occurs in the reverberation chamber will be avoided. Sensitivity, linearity and directivity measurements can be conducted. Using different fibre coatings is planned in future experiments in order to investigate their effect on sensitivity of the transducer.

In long term, there is number of questions and problems to resolve:

- improving spatial resolution of the system which currently is only 1m, possibly by using special geometric arrangement of the fibre,
- measuring and possibly improving linearity and noise capabilities,
- quantifying phase error between sections of the fibre,
- testing stability of the system in terms of sensitivity and linearity over long periods of time,
- improving sensitivity by using different materials for fibre coatings and the fibre itself,
- how to correctly model vibro-acousto-optic interaction analytically and numerically,
- accurate calibration of the system in order to measure absolute physical quantity,
- investigating how different geometrical arrangements will affect performance of the system,
- correct interpretation of measured data for different sound fields,
- possible tailoring of the system for specific applications in order to reduce cost of the system,
- improving signal-to-noise ratio,
- improving signal processing of the data,
- investigating accuracy of phase response between fibre sections to assess its suitability to accurate sound field measurements.

8 CONCLUSION

Distributed Acoustic Sensor based on Rayleigh backscattering and Phase Optical Time Domain Reflectometry could offer great possibilities for acoustics and audio engineers. However more research needs to be done to ensure that this technology meets accuracy requirements for advanced acoustic testing.

9 REFERENCES

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