# Quasi-distributed Vibration Analysis of a Cantilever Beam Using OFDR and Weak Reflectors

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**Abstract:** This work evaluates the performance of a quasi-distributed in-line velocimeter based on OFDR and weak reflectors to measure vibration every 10 cm, using a cantilever beam under free-end damping and during an impact-hammer test.

## 1. Introduction

Distributed and quasi-distributed acoustic and vibration sensing (DAS/DVS) are recently attracting a lot of interest due to their high applicability in industrial and civil-engineering applications, such as structure health-monitoring or predictive maintenance [1]. A wide range of these solutions employ time domain reflectometry to perform distributed measurements along several tens of kilometers with spatial resolutions in the meter order [2]. Another method to perform distributed measurements, but with higher spatial resolution, is based on optical frequency-domain reflectometry (OFDR), which can offer strain measurements with resolutions under the millimeter. It has been demonstrated that OFDR is also applicable for vibration sensing based on dynamic strain measurement at high repetition rate [3], but this requires of high-end equipment, which also limits the maximum detected frequency. Other approaches can detect vibration of a few points along the fiber employing cross-correlation [4]. Instead of using the Rayleigh scattering to perform the continuous detection, some works proposed the use of reflecting sensing elements. For instance, long fiber Bragg gratings can be used to evaluate dynamic strain with resolutions under 1 mm along 20 m on an aircraft fuselage [5] or a helicopter blade [6]. A quasi-distributed solution was proposed by the authors, using weak reflectors and an OFDR to detect frequencies up to 30 kHz using a low repetition-rate laser [7]. Moreover, a demodulation based on the short-time Fourier transform (STFT) evidenced the ability of the solution to perform velocity measurements at 2 kHz with a low repetition-rate laser, high fidelity, high configurability, and a linear response to arbitrary perturbations [8].

In this work, we evaluate this technique to be used for the vibration analysis of structures; due to its capability to measure high amplitude and arbitrary-waveform events. A series of experiments have been carried out in this regard, using a cantilever beam to measure free-end damping but also to evaluate the response under an impact-hammer test. Preliminary results evidenced a correct behavior of the system, and the ability to detect the first four bending modes. To perform the experiments, a 1.5 m-fiber was employed with 15 weak reflectors located every 9-10 cm, and 11 accelerometers were used for the validation.

## 2. Principle of operation

The technique employs an optical frequency-domain reflectometer to interrogate a fiber optic section with an array of weak reflectors as in [9]. In this manner, a highly coherent tunable laser is split and injected to an auxiliary interferometer and to the main interferometer with the fiber under test (FUT), as shown in Fig. 1 (a). The sensing fiber contains a number of weak reflectors that define the sections of the fiber that will be measured. Simplifying, the light reflected along the fiber interferes back in the coupler, generating an interferogram composed by the contributions of all the reflected (and backscattered) light. Then, under stationary conditions, a reflectivity vs distance analysis can be attained by using a frequency-to-time transformation such as the fast Fourier transform (FFT). However, under dynamic conditions, the light suffers a frequency change due to the Doppler shift. This effect is exploited to detect stimulus occurring along the fiber.

To perform the detection, the interferogram retrieved from the fiber with the reflectors is processed using the STFT. Since the position of the reflectors is frequency-dependent, the changes induced by the Doppler effect in the interferogram are perceived as a virtual change in the reflector's position, as can be seen in the experimental results. This variation is proportional to the velocity of the perturbations occurring in the fiber between the coupler and the corresponding reflector. Then, the perturbation happening between reflectors can be calculated just by subtracting the previous reflector velocity to the actual one [7,8]. However, in order to compare the performance of this system with conventional technologies such as accelerometers, the compensation is not required. Thus, the velocity change induced by the accumulated deflection on the cantilever will be employed for the vibration measurements.

## 3. Experimental setup

The experimental setup can be split into different parts. First, the OFDR employed offered a 10 m distance range, with laser tuning speeds from 5 to 80 nm/s with a maximum wavelength range of 100 nm. The digitalized interferogram was then processed using a STFT to evaluate the frequency shift of the reflectors due to the cantilever movement. The demodulation parameters were set to obtain a final spatial discrimination of 0.5 mm. The sensing fiber consisted of a standard single-mode fiber with 15 weak reflectors spaced 9-10 cm, for a total length of 1.4 m approximately. Note that the spatial resolution of this technique is defined by the distance between reflectors.

The weak reflectors were created using a fusion splicer Fujikura FSM-100P+ with the parameters set to create an imperfect fusion that induced a weak reflection in the transition. The reflectors were then protected with an acrylate coating using a Fujikura FSR-05 recoater. The sensing fiber was then fixed along the cantilever beam using adhesive tape as depicted in Fig. 1 (b). The position of the reflectors $R_1$ to $R_{15}$ was 0, 93, 188, 275, 376, 478, 574, 671, 769, 888, 989, 1093, 1189, 1288 and 1415 mm respectively, referenced to the position of the fixed point. Together with the fiber, 11 accelerometers Brüel & Kjær, Type 4507-B ($A_1$, $A_2$, …, $A_{11}$) were placed as reference at the reflector positions $R_1$, $R_2$, $R_3$, $R_5$, $R_6$, $R_8$, $R_9$, $R_{11}$, $R_{12}$, $R_{14}$, $R_{15}$. A picture of the experiment arrangement can be seen in Fig. 1 (b), evidencing the low impact of the fiber optic solution regarding installation and cabling. Finally, the cantilever consisted of an Aluminum 5052 beam with a length of 150 cm, a width of 10 cm and a thickness of 1 cm.

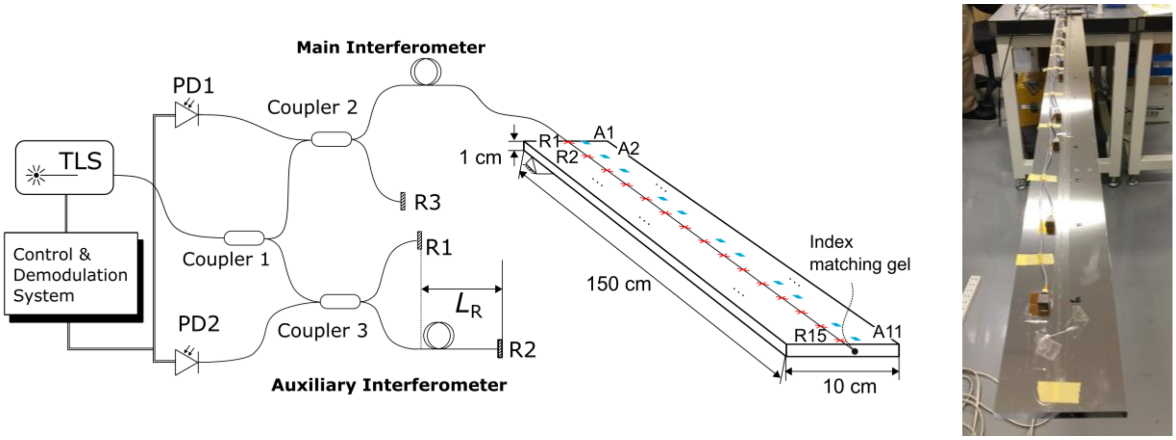

Fig. 1. (a) Schematics of the setup and (b) picture of the experiment arrangement.

## 4. Results

In order to evaluate the capabilities of the technique regarding vibration analysis, two different sets of experiments were carried out. First, the damping of the cantilever was evaluated under different forces applied at the end of the beam. In the second series of experiments, an impact-hammer test was carried out. Note that this work focuses on the performance of the optical system; further work is being done regarding the complete modal analysis.

### *4.1. Free-end damping*

First, the setup was tested under free-end damping condition by applying and releasing a force placed at the tip of the beam. The spectrogram presented in Fig. 2 (a) depicts the damping induced after the release of a 0.7 kg mass, for a laser tuning speed of 20 nm/s and a 3 second duration. It can be clearly seen the start of the oscillation after the release, with the different components induced by the individual bending modes. Moreover, it can be seen the variation of the mode contributions along the fiber/beam length. Figure 2 (b) presents the results after the ridge detection of the spectrogram shown in Fig. 1 (a). Note that in order to perform a complete vibration study, it is required to measure the velocity of each reflector with respect to the fixed end. In order to obtain absolute velocity elongation changes, the distance axis should be zeroed under stationary condition, and then a conversion distance-velocity should be done as in [8], considering the tuning speed of the laser and the emission frequency.

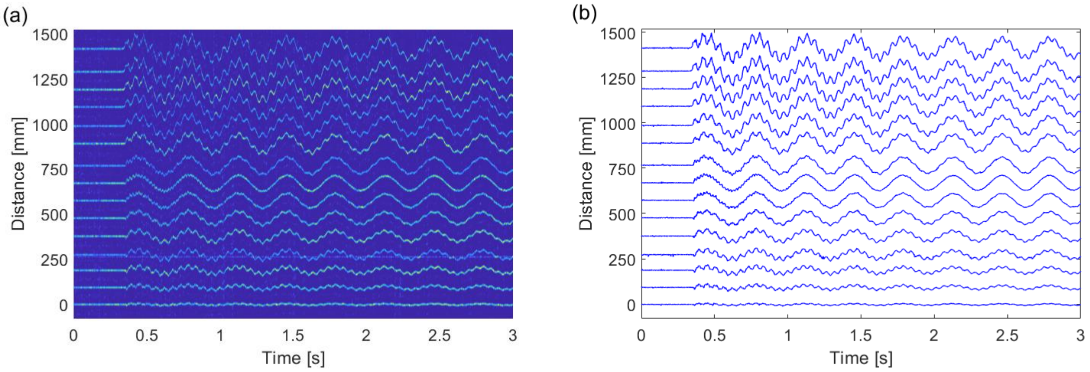

Fig. 2. (a) Spectrogram measured after the release of a 0.7 kg mass and (b) the demodulated signals.

Then, different forces were induced by attaching 0.3, 0.5, 0.7 and 1.0 kg masses at the further end of the beam and releasing them. Figure 3 shows the measured spectrogram with the demodulated signal overimposed in yellow for the sake of clarity and the time axis zeroed at the release time. As expected, it is a clear increase of the deflection with higher forces. It is worth noticing that the system is able to demodulate the signal at each reflector without crosstalk even in the case of the 1.0 kg mass, when the signal from some reflectors virtually crosses the real position of the others. This is an interesting feature of this technique, and it is due to the fact that close reflectors have little accumulated variation between them. Then, the limit in the distance between reflectors will be mainly imposed by the maximum change to be measured between reflectors and the parameters of the STFT demodulation.

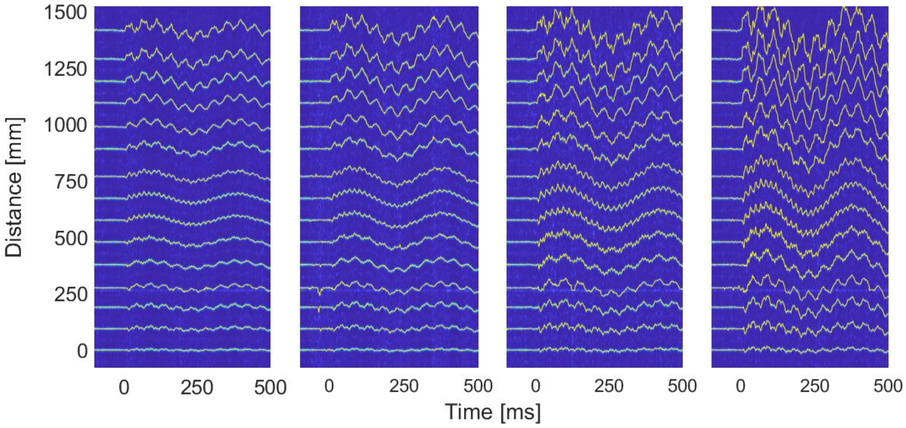

Fig. 3. Spectrogram measured after the release of a 0.3, 0.5, 0.7 and 1 kg mass respectively.

### *4.2. Impact-hammer tests*

In the second set of experiments, three series of impact-hammer tests were carried out. The impact-hammer test consists of the excitation of a structure to extract its harmonic information, including natural frequencies, modal damping ratios and modal shapes, usually by means of accelerometers. In this experiment, a sensorized hammer was used to hit the beam while measuring the position and force of the impact. Meanwhile, the vibration generated was recorded by the OFDR system with the 15 reflectors and by a set of 11 accelerometers.

Figure 4 (a) depicts an example of the spectrogram obtained from one of the impacts using a laser tuning speed of 20 nm/s, with the demodulated signal overimposed in yellow. In contrast to the free-end damping results, there is a *high* velocity impact that initiates the vibration that also induces high frequency components. It can be seen that some artifacts are present in the demodulated signal at the impact time due to the high velocity change. However, even if the signal almost reaches the neighboring reflectors, the ridge detection is able to track the signal again. Figure 4 (b) shows a detail of the spectrogram and demodulated signal at the 15th, 8th and 3rd reflectors. It can be seen that the system is able to detect high-frequency modes. The natural frequencies of the 1st to 4th bending modes were calculated theoretically, resulting in 3.4, 21.0, 59.0 and 115.7 Hz, respectively. These values were corroborated by the reference accelerometers, that offered frequencies of 3.3, 21.0, 59.4 and 116.1 Hz. On the other hand, the frequencies measured by the fiber optic setup were 3.3, 20.8, 58.1 and 114.1 Hz, successfully matching with the given by accelerometers and the theoretical values.

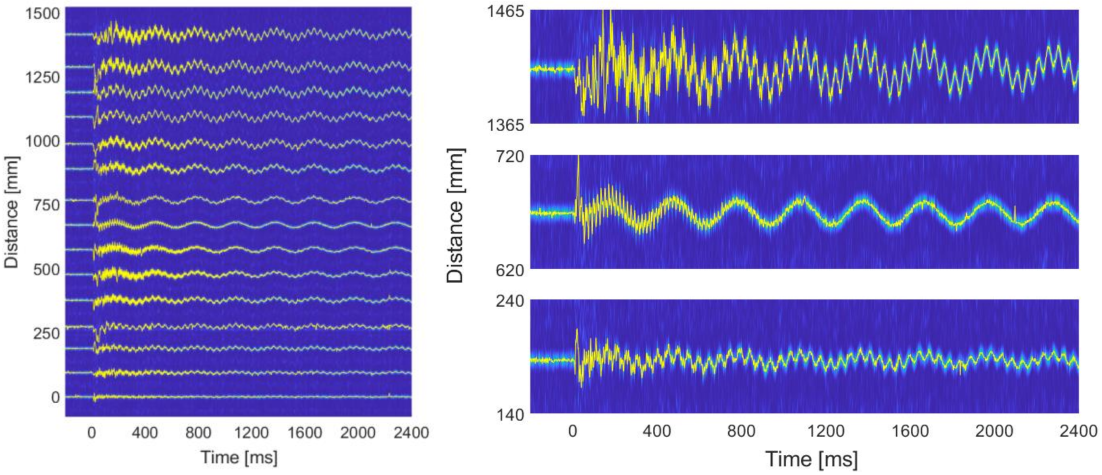

Fig. 4. (a) Spectrogram measured after one impact and (b) detail at the 15th, 8th and 3rd reflectors.

## 5. Conclusions

In this work, the vibration occurring in a cantilever beam was measured using an OFDR with an array of weak reflectors acting as in-line velocimeters. The sensing fiber consists of 15 weak reflectors created with a fusion splicer in a 1.5 m fiber. In this manner, the accumulated deflection change of the cantilever was measured every 10 cm. Two different experiments were carried out, the free-end damping using different forces at the end of the beam, and an impact-hammer test. An initial analysis evidenced a correct behavior of the technique, and the natural frequencies measured by the OFDR matched with the obtained both theoretically and by a set of 11 accelerometers.

Some of the main advantages of this technique include the low impact and easy installation and cabling in the structure (compared to accelerometers), the ability to monitor multiple sections with high spatial resolutions without crosstalk, or the high configurability (both in terms of sensing arrangement and software). On the other hand, some areas of improvement have been detected, such as the need of a simple and repetitive manner to create weak reflectors or the need of a deeper study of the impact of the processing parameters in the demodulated signal. These preliminary results will lead to a deep analysis of the performance of the system, by carrying out a complete modal analysis and comparing it with the provided by high-end accelerometers. Further work is being done in this regard.

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