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Photo-vibrational sensing of trace chemicals and explosives by long-distance differential laser Doppler vibrometer

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ABSTRACT

Photoacoustic/photothermal spectroscopy is an established technique for trace detection of chemicals and explosives. Normally high-sensitive microphone or PZT sensor is used to detect the signal in photoacoustic cell. In recent years, laser Doppler vibrometer (LDV) is proposed to remote-sense photoacoustic signal on various substrates. It is a high-sensitivity sensor with a displacement resolution of $<10\text{pm}$. In this research, the photoacoustic effect of various chemicals and explosives is excited by a quantum cascade laser (QCL) at their absorbance peak. A home-developed differential LDV at 1550nm wavelength is applied to detect the vibration signal at 100m. A differential configuration is applied to minimize the environment factors, such as environment noise and vibration, air turbulence, etc. and increase the detection sensitivity. The photo-vibrational signal of chemicals and explosives on different substrates are detected. The results show the potential of the proposed technique on detection of trace chemicals and explosives at long standoff distance.

Keywords: trace chemicals & explosives, photoacoustic, laser Doppler vibrometer, standoff detection, and spectroscopy

1. INTRODUCTION

The ability to rapidly detect and identify hazardous materials, such as explosives, is a key technology which would facilitate security screening in the global effort against terrorism. Recent R&D works focuses on technology to perform standoff sensing of hazardous materials in the open environment without any sample preparation. Photoacoustic/photothermal (PA/PT) techniques can provide sensitive non-contact solutions to overcome this challenge at meaningful standoff distance. Photoacoustic (PA) effect was discovered more than hundred years ago and was first reported in year 1880 [1]. Since last century, PA spectroscopy (PAS) has been applied in many applications for solids [2], liquids and gases [3] evaluation. Conventional PAS require prior preparation of analyte samples, and the measurement is conducted within a controlled environment, such as a well isolated photoacoustic cell. The response signal is captured either by a highly sensitive microphone, or any other forms of sensor located within close proximity or even in direct contact with the sample. Hence, commercial PAS equipment limits the technique in a laboratory environment. Conducting PAS in the open environment at a standoff distance is extremely challenging, due to the tremendous transmission losses of acoustic waves in air [4]. Even with a high-sensitivity microphone array coupled with a large parabolic sound reflector array, the maximum detection distance reported is only 12 meters [5].

Two recent research outputs, however hold promise to overcome the inherent limitations associated with PAS, were applied for standoff detection of chemicals and explosives. Firstly, technological advances of quantum cascade laser (QCL) enabled its use as a practical excitation source due to its high power, broadly tunable wavelength in mid-IR range and compact size over other light sources such as optical parametric oscillator (OPO) [6]. Secondly, noncontact optical detection techniques, such as thermal imaging and laser interferometry became an established method for standoff detection of PA/PT signal [7] in open environment. Cho etc. reported a QCL system as the excitation laser placed at 0.5m from the explosive targets, and a coherent detection system using a CW probe laser at 1550nm wavelength and realized a 5-meter detection of optical phase shifting due to PA/PT effects [8]. By measuring the optical phase shifts due to PA/PT effects at several wavelengths, an absorbance spectrum related to the explosive material was obtained.

Recently a conventional and mature interferometric system, laser Doppler vibrometer has been applied to detect the photo-vibrational signal on solid and liquid due to PA effect [9, 10]. It is observed that the spectra obtained coincide well

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with absorbance spectra of various substances. The standoff distance of LDV will influence the received power of reflected beam only, thus affecting the signal noise ratio (SNR) of interferometric signal, which may then increase the noise floor and reduce the sensitivity of the detection, but it will not affect the phase change detected due to PA/PT effect. The amplitude and frequency of vibration signal retrieved depends only on the frequency (or phase) shift of the reflected object beam, and not the received power. Hence, when the SNR of interferometric signal is acceptable by the demodulation system, the intensity of vibration signal retrieved will be the same. This is the distinctive advantage over other sensors such as microphone, for which the intensity of acoustic signal detected is inversely proportional to detection distance. Recent research [11] proved that LDV can be applied to detect photo-vibrational signal at 100m standoff distance.

In this study, a home-developed long-distance differential laser Doppler vibrometer (DLVDV) was applied to detect the photo-vibrational signal 100m away. A QCL with a chopper was adopted as the excitation source. A typical explosive, HMX (also called Octogen, formula: $C_4H_8N_8O_8$) on aluminum substrate with concentration of $10\mu\text{g}/\text{mm}^2$ was tested and the obtained photo-vibrational spectrum was compared with FTIR spectrum. The result show the proposed system can be applied for trace explosives detection at a meaningful safe distance.

2. PA SPECTRA MEASUREMENT USING LONG-DISTANCE DLVDV

2.1 Photo-vibrational signal

In this study, a differential laser Doppler vibrometer was applied to measure the periodic change of the optical path length (OPL) due to PA/PT effect when specimen was excited by an intensity-modulated QCL laser source with scanning wavelengths in the infrared range. The variation of OPL of the probing laser beam was then converted to vibration amplitude whose frequency equals to the modulation frequency of excitation laser. The theory behind the interpretation of photoacoustic signals was developed by McDonald and Westsel Jr. [2] on homogeneous bulk solid or liquid materials. However, for other forms of material sample such as loose powders, thin film or even chemical residues, the conversion efficiency of laser power to signal intensity is too complicated to be simulated and expressed mathematically in one equation. It is also dependent upon many other factors related to the morphological, thermo-chemical, and transport properties of the chemicals, substrate and air mass [8]. Several factors were identified to contribute concurrently towards any change of OPL in Ref.[11].

The photo-vibrational signal detected by normal LDV due to localized surface displacement and refractive index change of surrounding air layer can be expressed as [8, 9]

$$\Delta\phi \approx \frac{4\pi}{\lambda_{LDV}} (\Delta n_a \mu_a - n_a \Delta L) \approx \frac{4\pi \cdot \Delta T}{\lambda_{LDV}} \left[\left(\frac{dn}{dT} \right)_a \mu_a - n_a \mu_s \beta_s \right], \quad (1)$$

where ΔT is the temperature rise associated with periodic heating of the illuminated region by the excitation laser, and ΔL is the thermo-elastic expansion of the chemical. λ_{LDV} is the wavelength of probe laser in LDV, in our case $\lambda_{LDV} = 1550\text{nm}$. n_a is the refractive index of air; μ_a and μ_s are the air and chemical thermal diffusion lengths, respectively, and β_s is the linear thermal expansion coefficient of the chemical.

2.2 Excitation laser

The PA/PT effect is initiated by a chemical absorbing periodically modulated electromagnetic radiation. In this study, MIRcat-1200-1824, a multiplexed broadly tunable laser system from Daylight Solutions is used to excite the PA effect of the chemicals. It contains two QCL modules whose tuning ranges are from 6.89 to 7.55 μm and 7.65 to 8.5 μm , respectively. The maximum CW power of these two modules are >150mW. In addition, a red laser is aligned with QCL modules for aiming purpose. Water cooling is necessary for CW mode, especially in Singapore, as the working temperature of QCL is 17°C only. Figure 1 shows the MIRcat system and its output power of CW mode and pulsed mode. In our experiment, CW mode was applied and an optical chopper is applied in front of the laser to modulate the intensity. The disadvantage of using optical chopper is the power of QCL illuminated on explosives is reduced by 50%.

Figure 1. MIRcat QCL system from Daylight Solutions and its output power at CW and pulsed mode.

2.3 Home-developed long-distance Differential LDV

The optical configuration of our home-developed long-distance differential LDV is not same as conventional differential system. In conventional differential LDV, two object beams interfere with each other, and one detector is adopted to capture the interference signal. No reference beam is needed. The advantage of conventional differential configuration is that the common vibration detected by two object beams will be cancelled. In addition, laser noise can also be eliminated. Unfortunately, the conventional differential configuration cannot be applied in long distance detection, as the received power of two object beams are too low (in several 10^{-1} nW range), and the interference signal of these two object beams cannot be detected even an avalanche photodetector is used. Hence, a new differential configuration using two detectors is adopted. Fig. 2 shows the schematic layout of optical design for long-distance differential system. Two reflected object beams interfere with two reference beams respectively, and two avalanche photodetectors are applied to capture the interference signal from two sensing heads. These two signals are demodulated by a home-developed two-channel demodulation system with same time clock. The time-delay between two channels is <10ns. The common environment vibration detected by two sensing heads can be eliminated by subtraction of two retrieved signals. The amplitude of common environment vibration is in the range of several micrometers to several tens of micrometers, and normally the frequency range is <3kHz. Unfortunately, this configuration cannot cancel the laser noise, thus the noise floor of the whole system remains the same as a single-point system. Fig. 3 shows the front view and rear view of the system. Two sensing heads are mounted on a solid platform to ensure the vibrations of two sensing heads due to environment factors are almost same.

Figure 2. Schematic layout of optical design of differential long distance differential laser Doppler vibrometer

Figure 3. Front view and rear view of long distance differential laser Doppler vibrometer

3. EXPERIMENTAL ILLUSTRATION

Figure 4 shows the schematic layout of optical arrangement at one end of 100m distance along the corridor in the open air. The QCL laser is running with CW mode. An optical chopper is applied to modulate the laser intensity. The frequency of optical chopper is 1300Hz. It can be observed that there is no environment vibration at this frequency. Two adjustable mirrors are used to reflect two probe laser beams downwards, one on the test sample, another on solid base. The vibration signal obtained is the velocity difference of these two points. A third reflective mirror is adopted to reflect the QCL downwards, overlapping with the QCL laser spot on the test sample. The size of QCL spot is around 2mm. The spot size of focused probe laser is around 6mm at 100m with a 4-inch beam expander. With the aid of aiming red laser and NIR sensing card, two laser spots are overlapped on test samples by adjusting the knob of reflective mirrors. The explosive tested is HMX (Octogen), which is a powerful and relatively insensitive nitroamine high explosive. The substrate is aluminum and the concentration of HMX is $10\mu\text{g}/\text{mm}^2$. The environment temperature is around 32°C , humidity is $>90\%$. The environment sound level is around 60 decibel, mainly from the air blower in cooling tower of the buildings and the water chiller of the QCL.

Figure 4. Experimental setup for photoacoustic signal detection at one end of 100m;

4. RESULTS AND DISCUSSIONS

At each wavenumber, the amplitude of vibration velocity can be obtained by LDV in 2-second integration time. The longer integration time leads to an average of more instant velocities and the readings become more stable. There is always a tradeoff between the accuracy and integration time. The vibration amplitude obtained at each wavenumber is normalized by QCL output power, which is calibrated before experiment. The normalized amplitude is plotted against wavenumber and a photo-vibrational spectrum can be obtained. Fig. 5(b) shows the photo-vibrational spectrum of HMX obtained at 100m standoff distance. Fig. 5(a) is the IR absorbance spectrum of HMX from NICODOM explosive

database. It can be observed the characteristic peaks on both spectra coincide well. Fig. 6(a) shows the linear FFT spectrum of velocity obtained at wavenumber of 1270cm^{-1} with 2-second integration time using DLDV. Besides the high peak of photo-vibrational signal at 1300Hz , a harmonics at 2600Hz can be observed, together with some residue environmental noise. Fig. 6(b) shows the linear FFT spectrum obtained by single-point LDV. The comparison shows better SNR can be obtained using DLDV. Fig 7 shows the short-time Fourier analysis of the detected vibration signal from 1200Hz to 1400Hz . The ridge at 1300Hz and its amplitude variation along time-axis can be observed.

Figure 5. (a) IR absorbance spectrum of HMX from NICODOM Ltd; (b) Normalized vibration velocity detected by DLDV at various wavenumber on HMX powder ($10\mu\text{g}/\text{mm}^2$).

Figure 6. (a) Spectrum of vibration detected by long-distance (a) DLDV (b) single-point LDV at 100m on trace HMX powder ($10\mu\text{g}/\text{mm}^2$) with aluminium plate.

Figure 7. Short-time Fourier analysis of vibration signal obtained by DLDV from 1200Hz to 1400Hz.

It is worth-noting the amplitude of photo-vibrational signal obtained by LDV may be fluctuating due to the environment factors. The proposed differential LDV can eliminate the effect of the common environment vibration at certain level but unfortunately the noise floor of the detection is almost same as single-point LDV. Longer integration time may stabilize the reading and eliminate the noise floor, but it may also reduce the efficiency of detection in real applications. In addition, it is not necessary to obtain photo-vibrational spectrum of explosives or hazardous chemicals in real applications. Detection of photo-vibrational signal at one or two characteristic wavenumbers is enough to raise the alarm for further investigation. Fortunately many explosives share the same characteristic peak in absorbance spectra due to the similar molecular structures. For example, RMX, RDX and PETN have same characteristic peak at wavenumber of near 1270cm^{-1} .

5. CONCLUSIONS

In this paper, a home developed laser coherent detection system ----- a long-distance differential laser Doppler vibrometer is applied to detect the photo-vibrational signal on explosive due to photoacoustic effect at 100m standoff distance. A QCL is used to excite the PA/PT effect of HMX with concentration of $10\mu\text{g}/\text{mm}^2$ on aluminum substrate. The obtained photo-vibrational spectrum matches well with database from NICODOM Ltd. The experiments demonstrate the detection of PA effect at a meaningful safe distance by a differential LDV in an imperfect environment, which also show its technical potentials in real applications.

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