TARGET RECOGNITION BY VIBROMETRY

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Abstract: *By using doppler technique and an optical laser radar it is possible to measure vibrations from surfaces and analyse their vibration spectra. One can then distinguish between different types of vehicles by their spectra, which indeed can be said to act as a fingerprint.*

INTRODUCTION

There are active methods like analysis of the radar echo as well as passive systems such as evaluation of the thermal image. In a sharp attack it is of great importance not to be detected by the enemy and therefore a passive system is preferable. Characterization by vibrometry is however an active method but the signature is very valuable and it is thererfore, at least for a short time interval, worth running the risk of being discovered. The disadvantage by the active nature of the system is well compensated by the fact that it is difficult to jam.

There are a number of factors which must be considered when using laser vibration sensing to identify airborne and ground based vehicles. The system will operate at long distances and reflections from clouds, rain, turbulence etc have to be taken care of. If the laser radar (LADAR) system is mounted on an fighter aircraft, tank, truck, or any other mobile weapon system, the vibrations from this platform may interfere with the fingerprint from the target if they are in the same frequency band. Furthermore, as the mobile weapon system is moving a doppler shift will be introduced, along with the one caused by the target, and they need to be separated in the signal processing. Glint or diffuse targets as well as a good camouflage yields different reflections.

There are a number of alternatives to choose among when designing a laser radar system. Is it going to be a homo or heterodyne system, what wavelength and type of laser shall be used and so on. Hardware design is just one half of the issue. An effective software is vital to extract the information needed for recognizing a target signature.

THE SYSTEM

The laser system most provide the desirable laser energy for both the transmitted laser beam and a reference local oscillator (LO).

$$f_{laser} = \frac{c}{\lambda_{laser}} \qquad (1)$$

The transmit and receive head, where the output of the laser is fiber coupled into, uses a beamsplitter to split out approximately 10 % of the beam for the LO signal. The LO signal is then shifted by an electro-optic modulator. The remainder is expanded and transmitted through a telescope. A similar and co-aligned receive telescope collects the returning beam, backscattered from the target. Finally, the returning beam and the LO beam are combined onto a photo-diode detector.

A traditional FM-discriminator approach can be limited by laser signature characteristics and degrades the performance for two reasons. Firstly, the laser coherence might be poor which results in laser phase noise. Secondly, since the laser wavelength is small compared to the height of the surface variations of the target, the received laser energy is diffused by speckle fading.

Both the amplitude and phase of the reflected laser signal contains target vibration information. The phase imparts a frequency modulation onto the reflected waveform, which require FM demodulation to extract the proper vibration information. However, the time-varying speckle pattern acts as noise in traditional FM demodulation techniques and decreases the performance significantly. A spectrogram approach can process both the amplitude and phase information in the presence of laser speckle and laser phase noise.

The spectrogram processor is built up according to the block diagram in Figure 1. The LO laser signal is optically mixed with the FM-modulated return signal and is therefore said to be offset heterodyne detected. The offset refers to the shift whereas heterodyne means that there are two light frequencies, in this case coming from the same source but splitted in two, one of them shifted. Another alternative would be to have a homodyne system where the signal and reference beam has got the same frequency and use two detectors with a $\pi/2$ phase shifter to get the proper sign of the target motion.

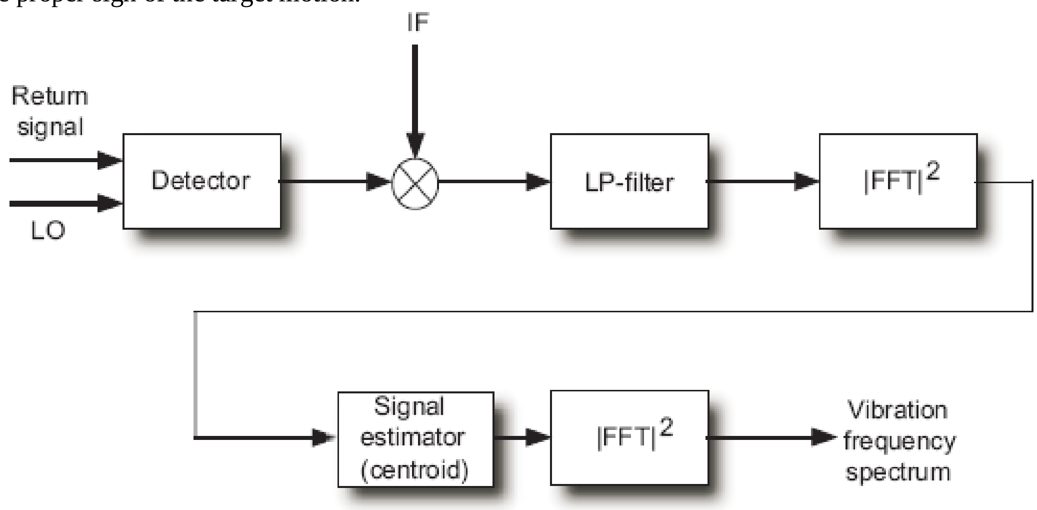

Figure 1. Block diagram of CW spectrogram processor.

After LP-filtering the mixer output, the signal is sampled with a digitizer, where the A/D conversion rate is carefully chosen to be consistent with the expected bandwidth of the FM modulated return signal. N samples are collected to form the first sample set which is then input into an FFT. A centroid algorithm then estimates the frequency for that particular sample set and this correlates to a velocity. The carrier frequency will be centered around zero since only stationary targets are to be considered here. A time history of such velocities is built up and put into a second FFT where the final output is the vibrational frequency spectrum. The Nyquist frequency is half the sample rate and with velocity estimates.

The return signal $s_{ret}(t)$ has to be shifted to a lower frequency region where the signal processing is more suitable. This is done by optically mixing the returned laser signal with the electro-optically frequency shifted LO signal $s_{LO}(t)$.

$$f_{LO} = f_{laser} + f_{eom} \tag{2}$$

$$s_{LO}(t) = A_{LO} \cdot \sin(2\pi f_{LO} t) = A_{LO} \cdot \sin(2\pi (f_{laser} + f_{eom})t) \tag{3}$$

Assume a product of two general signals

$$\sin(\omega_1 t)\sin(\omega_2 t) = \frac{1}{2}[\cos(\omega_1 - \omega_2)t - \cos(\omega_1 + \omega_2)t\,] \tag{4}$$

then the product is the sum and difference frequencies and if ω_1 and ω_2 are large with a small difference $(\omega_1 - \omega_2)$ then the first term is a low frequency term which may be extracted by means of a LP-filter.

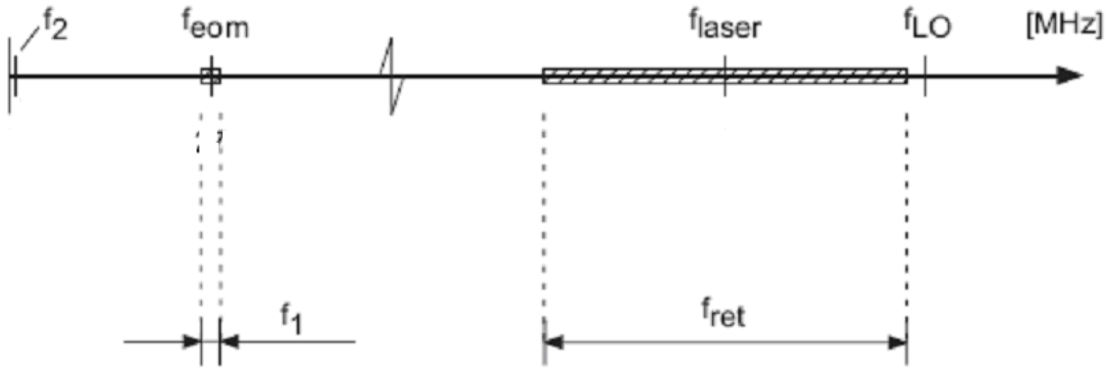

Figure 2. Frequency shifting and mixing with the IF frequency.

The return signal includes the laser frequency, a doppler shifted frequency, f_{laser}, due to radial target motion and a surface vibrational doppler frequency, f_{vd}, where the two Doppler frequencies can be positive or negative. The frequency of the returned signal is within the interval.

$$(f_{laser} - f_{rd} - f_{vd}) < f_{ret} < (f_{laser} + f_{rd} + f_{vd}) \quad (5)$$

For a stationary vehicle f_{rd} is zero.
Consider the equation for the radial doppler shift, where *v* is radial velocity,

$$f_{laser} = \frac{2v}{\lambda_{laser}} \quad (6)$$

which shows the radial doppler shift for each meter per second that the vehicle is moving. A vehicle moving with a speed of 27 m/s (97 km/h) would then cause a radial doppler shift of 27 MHz and this is above the maximum speed for the vehicles considered here. In a heterodyne detection system there is a need for a modulation frequency high enough to always get a positive f_1 frequency.

$$f_1 = f_{LO} - f_{ret} = (f_{laser} + f_{eom}) - (f_{laser} \pm f_{rd} \pm f_{vd}) = f_{oem} \pm f_{rd} \pm f_{vd} = f_{laser} \pm f_{vd} \quad (7)$$

At the last step in the expression for f_1 the radial doppler shift is set to zero due to stationary targets and the vibrational doppler shift contribution is small compared to f_{oem}. Finally, f_1 is mixed with the intermediate frequency and the result, a low instantanous frequency, f_2, is LP filtered.

$$f_2 = f_1 - f_{eom} = f_{oem} \pm f_{vd} - f_{eom} = \pm f_{vd} \quad (8)$$

TIME FREQUENCY SIGNAL ANALYSIS METHODS

1. Linear time frequency representation

Time domain analysis by itself does not fully describe the nature of signals. Frequency domain analysis is an alternative description. A combination of the two domains has been available and of interest in signal processing for a long time. A signal, s(t), satisfies the superposition principle if it is built up by a linear combination of two signal components, $s_1(t)$ and $s_2(t)$, with constants c_1 and c_2.

$$s(t) = c_1 s_1(t) + c_2 s_2(t) \quad (9)$$

As the two domains are combined the time-frequency distribution of a signal can be described by a joint function, $T_S(t,f)$, of time t and frequency f. is called a time-frequency representation of the signal s(t). All linear time frequency representations (TFR), the wavelet transform and the short time Fourier transform (STFT), satisfy the superposition principle.

$$T_S(t,f) = c_1 T_{S1}(t,f) + c_2 T_{S2}(t,f) \tag{10}$$

The STFT is said to be a local spectrum since a time localization is obtained by pre-windowing the Fourier transform of the signal $s(\tau)$ with a shifted analysis window $\gamma(t)$.

$$T_{STFT}(t,f) = \int_{\tau} [s(\tau)\gamma^*(\tau - t)] e^{-j2\pi f\tau} d\tau \tag{11}$$

The analysis window, $\gamma(t)$, is centered around *t* and suppresses all signal features outside a local neighborhood of the time *t*. It is difficult to extract the frequency content of a signal in the time domain, especially for time-varying nonstationary multicomponent signals, perhaps with a combination of amplitude modulation (AM), frequency modulation (FM), and noise.

2. Quadratic time frequency representation

An energy distributed TFR, $T_S(t,f)$, can be interpreted by using the concepts of the instantaneous power, $p_S(t)$, and the spectral energy density, $P_S(f)$. The instantaneous power is represented by the squared magnitude of the signal,

$$p_S(T) = |s(t)|^2 \tag{12}$$

and the Fourier transform of the signal is beeing used to express the spectral energy density as

$$S(f) = F\{s(t)\} = \int_{-\infty}^{\infty} s(t) e^{-j2\pi ft} dt \tag{13}$$

$$P_S(f) = |S(f)|^2 \tag{14}$$

An integration over frequency and time respectively finally gives the energy distributed TFR, $T_S(t,f)$, as

$$\int_f T_S(t,f)df = p_S(t) = |s(t)|^2 \tag{15}$$

and

$$\int_t T_S(t,f)df = P_S(f) = |F\{s(t)\}|^2 \tag{16}$$

Note that this is true for an ideal case, an integration over frequency normally cause a loss of time resolution and vice versa. The signal energy, E_S, is obtained by integrating over the entire time-frequency plane.

3. Statistical peak distribution

The idea behind the statistical peak distribution method (SPD) is to divide the received signal into short time intervals, apply proper signal processing techniques, and compare the sets in a statistical manner. The benefits of this method is that it can be developed as a mathematical method in the sense that there is no need to analyse a visual 2D-plot but instead some statistical data is delivered by the algorithm. This is useful when it comes to automatization of the target recognition process. The answer to an operator of the system would be a target identification along with a presentation of the probability that the statement is true. The method works better the longer time the laser keeps track of the target since that means more information. The data files analysed here are up to two minutes long with a sample rate of 1 kHz.

The algorithm works in four steps;

- Detection of high amplitude peaks and their corresponding frequency
- Calculation of percentage appearance, or time of existence, for each peak
- Presentation of the time dependent amplitude variations for each specific frequency
- Separation of fundamental tones and overtones.

4. The modified FOA method

The original FOA method is a correlation method which uses the ambiguity function. Some modifications of the method has been made which ended up with a modified FOA method to be able to take care not only of stationary targets but also of radially moving targets, constantly or accelerating.

The FOA method can not demodulate signals with a carrier frequency. Modifying the method to first estimate the carrier frequency and then eliminate the carrier frequency by mixing the signal with a sinusoid, makes it possible to detect moving targets. Mixing the signal with a sinusoid centres the spectrum around zero as if there were no carrier frequency, like for a stationary target.

DIFFERENT ASPECTS FOR A CERTAIN VEHICLE

Based on a mixture of all four methods, as one method fails to locate the vibration frequencies in a particular data file another method works better and the result from that method is registered.

Three questions will be answered by this way of studying the result from the signal processing;

1. *Is the vibration frequencies independent of the laser beams point of impact with the targets body?*
2. *Which frequencies are common for a vehicle irrespective of what part of the body you analyse, i.e. which are the characteristic frequencies for a certain vehicle?*
3. *Which method is the most robust and reliable one?*

Often, two or more of the four methods present more or less the same result. Sometimes the methods come up with the same frequency peaks but the peak amplitude is different. Usually one frequency is dominant and much stronger than the other ones and for those cases the strongest peak is the same for all four methods. When the result varies a lot between the methods the result from the statistical peak distribution is registered since it seems to be the most reliable one. It is the essential to know the background information that has been used to draw conclusions from.

CONCLUSIONS

Each target has got a unique signature which is, with some reservation, possible to identify and classify. Different aspects has got certain influence on the vibration frequencies but the available amount of data most be enough to make a correct judgment whether or not it is possible to identify a target from other kind of angles and aspects. At least to be possible to classify vehicles, with the suggested “fingerprints”, for the aspects available.

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