Doppler Radar Detection of Mechanically Resonating Objects

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Introduction

The limitations of existing countermine technology have motivated the development of an acousto-electromagnetic technique for detecting landmines, pipes, and other buried objects [1]. This hybrid method exploits the acoustic resonance of an object to discriminate it from soil, plant matter, rocks, and other clutter that cause false alarms for GPR. An object is distinguished based on the Doppler signature imparted to radar signals scattering off the object's vibrating surface.

The present experiment was intended to verify that small vibrations in objects can be detected by a sensitive Doppler radar. Objects with known acoustic resonant frequencies are excited, and their Doppler signatures are measured using a CW radar system. When the object surface retreats from the radar, the carrier is slightly red-shifted, and when the surface approaches the radar, the carrier is slightly blue-shifted. The amount of the shift varies as the surface oscillates, causing the instantaneous carrier frequency to likewise vary over time. In the resulting Doppler return, the carrier signal is frequency modulated by a pure tone.

Doppler Return

Tuning forks were selected as targets because of their spectrally-pure, high-Q acoustic resonances. A simple model for the radar return signal of a tuning fork is

$$s(t) = C\cos(2\pi f_c t - kz)$$

where $z(t)$ is the distance between the antenna and the tuning fork, and f_c is the carrier frequency. If the bars of the tuning fork oscillate back and forth in a direction radial to the antenna, then the accumulated spatial phase delay of the reflected signal is

$$kz = 2k(d + A\sin(2\pi f_a t)) + \pi$$

where f_a is the acoustic resonant frequency of the tuning fork and d is the distance between the antenna and the tuning fork. Inserting this time-varying phase back into $s(t)$,

$$s(t) = C\cos(2\pi f_c t - \frac{4\pi}{\lambda_c} A\sin(2\pi f_m t) + \varphi)$$

where φ is a constant phase term.

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To examine the effects of the tuning fork vibration on the spectrum of the return signal, we first observe that *s(t)* is frequency modulated, and if we neglect the phase φ, *s(t)* can be expanded using Bessel functions [2]:

$$s(t) = C\sum_{n=-\infty}^{\infty} J_n(\beta)\cos((2\pi f_c + n2\pi f_a)t)$$

$$\beta = \frac{4\pi \cdot A}{\lambda_c}$$

As is shown in Figure 1, only the first of these Doppler components ($n=\pm1$) is large enough to be detectable by a practical system.

The power of the first Doppler component at the receive antenna can be predicted using the radar equation weighted by $J_1(\beta)$,

$$P_r = \frac{P_t G_t G_r \lambda_c^2 \sigma}{(4\pi)^3 R^4}(J_1(\beta))^2$$

For purposes of this model, the tuning fork was considered to be a flat plate with a radar cross-section of

$$\sigma = \frac{4\pi(ab)^2}{\lambda_c^2}$$

and a resonant bar of dimensions *a x b* that was oriented perpendicular to the antenna beam. Because the amplitude of the tuning fork displacement varies along the length of the fork bar, the bar was broken down into 20 segments and $J_1(\beta)$ was calculated for each of them, resulting in a weighted RCS.

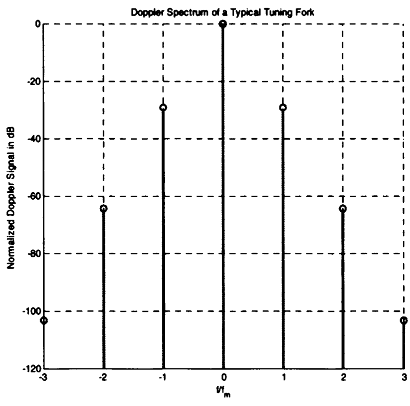

Figure 1 Doppler return components of typical excited tuning fork at 1.65 GHz. The peak vibration amplitude of the fork was estimated to be 1.75 mm.

Measurement

We set up an L-band CW radar to detect vibrating tuning forks in a clutter environment. A bistatic configuration was chosen to ensure adequate isolation between transmit and receive. An operating frequency of 1.65 GHz was chosen because it is low enough to propagate adequately through moist soil and yet high enough to yield a detectable Doppler response.

For our first dataset, tuning fork vibration was achieved by striking the forks with a rubber-tipped hammer. For our second dataset, a speaker was driven at the resonant frequency of a nearby tuning fork in order to remotely excite the fork vibration. In order to prevent cross-talk and leakage, the speaker was turned off just before data was collected using the radar. In each case, after the tuning forks were excited, a spectrally pure CW signal was transmitted from the Tx horn. The return signal was passed through a 30-dB Low-Noise Amplifier and mixed down to baseband.

The baseband signal was fed from the mixer to a lock-in amplifier that was configured to act as a spectrum analyzer in the DC to 2 KHz range. The lock-in amplifier allowed detection of very weak signals by applying band-pass filters around each frequency bin to be displayed. The band-pass filtering removed any thermal noise that was outside of the narrow band of interest, thereby providing a good SNR.

Because the kTB thermal noise power in a 1.2 Hz bandwidth is so small, the main obstacle to achieving a good SNR is the phase noise of the unmodulated carrier signal. In the region critical to our Doppler measurements, 100-to-2000 Hz off the carrier frequency, the power level of our source varied between -95 and -85 dBc. While these are relatively low power levels, a Doppler return may be so weak as to be eclipsed by this phase noise power; this underscores the need for a clean synthesizer.

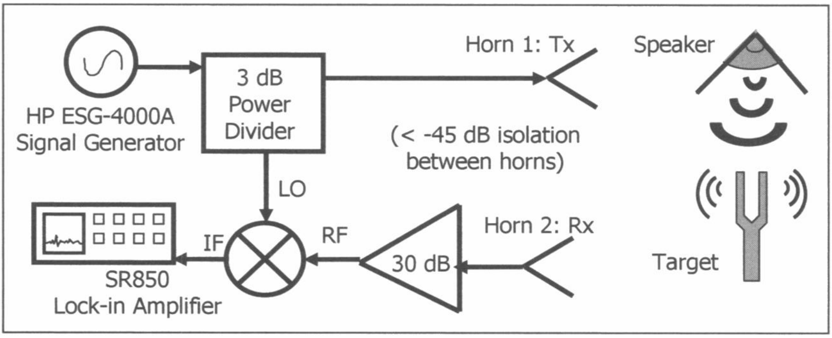

Figure 2 Diagram of the Doppler radar system.

Results

When the tuning forks were struck, prominent voltage peaks appeared in the read-out of the lock-in amplifier. Figure 3 shows the Doppler responses produced by hammer-excited 166 Hz and 274 Hz tuning forks placed 1.75 meters from the antennas. When we account for all losses in the radar, the radar equation calculation predicts a Doppler return of **-103.8 dBW**, or 45.6 μV, from the 166 Hz fork. This compares favorably to the measured values of **-104.7 dBW**, or 41 μV. This close agreement between measurement and prediction suggests that our model of the tuning fork RCS and motion-induced Doppler component is valid to at least a first order.

The Doppler radar system was decidedly less effective when the tuning forks were excited remotely using the speaker. Although a 2.6 μV response did occur at the expected frequency of 166 Hz, it was difficult to distinguish this response from adjacent noise and interference. These weak returns suggest that the acoustic coupling between the speaker and the tuning fork was too weak to result in detectable motion.

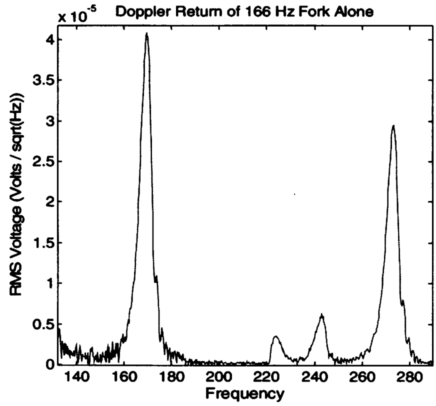

Figure 3 Very strong Doppler returns (>20 dB SNR) were obtained from tuning forks vibrating at 166 Hz and 274 Hz (41 and 30 μV, respectively), along with interference (a harmonic of 60 Hz).

Conclusion

Our Doppler radar succeeded in detecting resonant tuning forks even when the vast majority of the receive power was clutter. The primary limitation on our system's performance was not the sensitivity of the radar, but rather the ability to couple acoustic energy into the forks from a remote source. In order to remotely excite a detectable vibration in the tuning forks, one would need a better acoustic transducer than the speaker used in this study.

References:

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[2] B. P. Lathi. Modern Digital and Analog Communications Systems. New York: Oxford University Press, 1998.