1 Applications of Spectral Analysis

1.1 Introduction

Our aim is to apply qualitatively applications of spectral analysis to various signal processing problems in applied science, communication, control, and avionic/aerospace systems. In this way, we will be motivated to consider the problems of determining the complexity and implementation of spectral analysis by means of parametric and non-parametric modeling.

1.2 Modulated Frequency-Shifted Keyed (M-FSK) Modulation in Communication Systems

First, consider a simple communication system illustrating the use of frequency-shifted keyed (FSK) modulated signals. Consider the earliest well-known Bell System 103 type full-duplex modem used for low data rate (300 Baud rate or less) transmission between a computer terminal and a central computer developed in the 1960s. This problem models a two-way binary data communication system. That is, upon encoding the ASCII data from the terminal or computer (either 64 or 128 hypothesis signals) as 6 bits or 7 bits data (plus parity, start, and stop bits), the basic transmission system is modeled as a repeated binary channel.

The binary data of a "one" (called a *mark*) and a "zero" (called a *space*), from old telegraph notation, can be modeled as two sinusoids (also called "tones") of amplitudes A and frequencies f_1 and f_0 of duration T. That is, the received data are of the form

$$x(t) = \begin{cases} A \sin 2\pi f_0 t + n(t), & \text{"space"} \\ A \sin 2\pi f_1 t + n(t), & \text{"mark"} \end{cases} \quad 0 \le t \le T, \tag{1.1}$$

where $n(t)$ represents the noise on the telephone line. In fact, since the transmission is full-duplex, there are two sets of FSK signals of the form given in (1.1). One set represents that of the originate modem and the other represents that of the receiver modem. Indeed, the spectral contents of the telephone line may look like that of Fig. 1.1. The detector at either modem must declare the presence of one of the two transmitted tones. A suboptimum non-coherent receiver based on spectral domain filtering is less complex than an optimum coherent receiver. In high SNR conditions encountered in typical telephone lines, a non-coherent receiver is quite adequate.

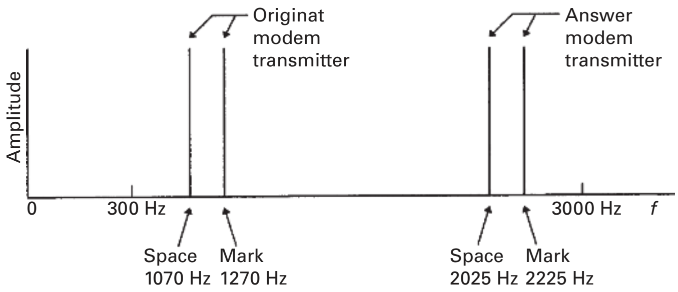

Figure 1.1 Full-duplex low data rate modem spectra

On the other hand, a general M-ary waveform is modeled by

$$x(t) = \begin{cases} A \sin 2\pi f_0 t + n(t) \\ A \sin 2\pi f_1 t + n(t) \\ \vdots \\ A \sin 2\pi f_{M-1} t + n(t) \end{cases} \quad 0 \le t \le T. \tag{1.2}$$

The M-ary FSK (M-FSK) waveform is a practical form of modulation permitting higher data rate transmission. Since the detection can be done non-coherently, its receiver structure (consisting of a bank of M bandpass filters) is simpler and it may be more robust to various system degradations and interferences compared to a coherent phase-shifted keyed (PSK) system. Of course, compared to an M-PSK system, an M-FSK system is less efficient from the SNR point of view.

1.3 CW Doppler Radar

Let the transmitted signal $s(t)$ be given by

$$s(t) = A \sin 2\pi f_0 t, \qquad -\infty < t < \infty.$$

Let the first-order approximation of the *range* be given by $R \approx R_0 + \dot{R}(t - t_0)$. The delay time is expressed by

$$\Delta t = \frac{2R}{c},$$

where c is the velocity of propagation. The received signal is given by

$$\begin{aligned} s_R(t) &= A_R \sin 2\pi f_0 (t - \Delta t) \\ &= A_R \sin \left(2\pi f_0 t - 4\pi f_0 \frac{R}{c} \right) \\ &= A_R \sin \left(2\pi f_0 t - 4\pi f_0 \dot{R} \frac{t}{c} - 4\pi f_0 \frac{(R_0 - \dot{R} t_0)}{c} \right) \\ &= A_R \sin \left(2\pi f_0 t + 2\pi f_{dt} + \theta_0 \right), \end{aligned}$$

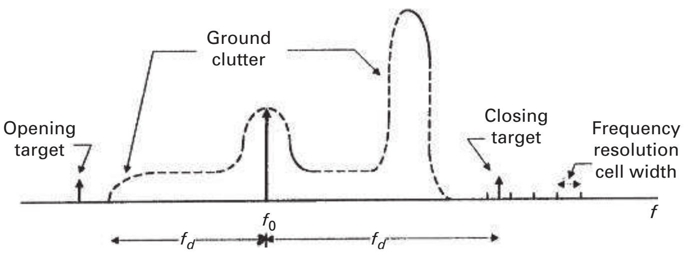

Figure 1.2 Spectral domain of an airborne Doppler radar receiver

where A_R is the received amplitude, $f_0 \equiv c/\lambda$, θ_0 is a fixed phase offset, and the "Doppler frequency" shift is defined by $f_d \equiv -2\dot{R}/\lambda$.

For a transmitted signal of frequency f_0, the received frequency is given by $(f_0 + f_d)$. When the target is *closing* (i.e., moving toward the transmitter), the range decreases and $\dot{R} < 0$, and thus the Doppler frequency f_d is positive. When the target is *opening* (i.e., moving away from the transmitter), the range increases and $\dot{R} > 0$, thus producing a negative Doppler frequency. Fig. 1.2 shows the spectral content of the receiver of an airborne Doppler radar. The ground reflection returns from all directions to produce the large band of "clutters" centered about the transmitted frequency f_0. The narrow width clutters centered about f_0 come from the ground patch essentially directly below the aircraft. The large clutter returns at the right edge of the band are due to the clutter returns in the mainlobe of the radar antenna. A fast-closing target may clear the clutter region and appear above the upper edge of the clutter region. Similarly, a fast-opening target may clear the clutter region and appear below the lower edge of the clutter region. Targets that appear in the clutter region may be much more difficult to detect than those in the clear regions. The size of the frequency resolution cell determines the resolution of the velocity of the target. The resolution cell is determined by the parameters of the data and the specific spectral analysis technique used in the radar receiver.

1.4 Speech Processing

Modern speech processing uses spectral analysis in many ways. Speech waveforms are non-stationary and at best can be modeled as quasi-stationary over some short duration of 5–20 ms. Speech can be considered as voiced (e.g., vowels such as /a/, /i/, etc.) or unvoiced (e.g., /sh/, etc.), or both. Time and frequency examples of a voiced waveform are given in Fig. 1.3 and those of an unvoiced waveform in Fig. 1.4. As can be seen, voiced waveform are quasi-periodic in the time-domain and thus harmonically related in the frequency domain. The fine structure of the spectrum is due to the vibrating vocal cord and the envelope structure (formant) is due to the modulation of the source with the pharynx and the mouth cavity. On the other hand, unvoiced waveforms are more random and spectrally broadbanded.

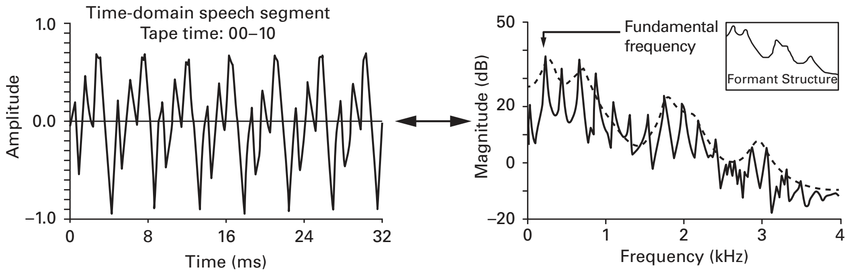

Figure 1.3 Time and spectral domains of a voiced waveform (IEEE Permission, Spanias, Proceedings of the IEEE Oct. 1994)

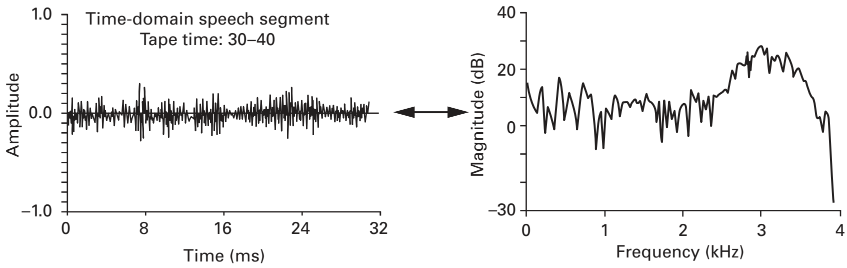

Figure 1.4 Time and spectral domains of an unvoiced waveform (IEEE Permission, Spanias, Proceedings of the IEEE Oct. 1994)

Various spectral analysis and synthesis techniques have been used to characterize speech waveforms. Autoregressive (AR) parameters based on an all-pole system for the modeling of a vocal tract based on the linear prediction (LP) technique was proposed in the 1970s. Since then, spectral techniques based on short-time Fourier transform (STFT) have been proposed. In the last four years, motivation for robust low-rate speech coding has led to the use of vector quantization (VQ) of LP coding (LPC). Quite sophisticated spectral analysis–synthesis techniques are used in modern code excited linear prediction (CELP) coding. In addition, spectral analysis techniques (e.g., STFT and wavelet techniques) have been proposed for voice recognition and speaker identification.

1.5 Other Applications

From classical spectroscopy, it is well known that different heated bodies emit different spectral radiations, and thus can be used for identification purposes. In radio astronomy, line and continuous spectra in the radio and x-ray band have been used for characterization of supernova stars. In atmospheric and oceanographic sciences, spectral contents of wind and ocean waves are used to characterize storm conditions. In earth resource satellites, different spectral optical and infrared bands yield information for earth resource explorations. In mechanical systems, spectral information characterizes different modes of vibrations. Prediction of bearing failure of induction motors based on stator current spectra lines has been used with success. In avionic systems, spectral analysis of radar reflected jet engine modulated (JEM) rotor blades has been used to identify the aircraft via its engine types. In medical sciences, spectral analysis of electroencephalograms has characterized schizophrenia, Parkinson disease, Huntington disease, and other neurologically caused illness. Spectral analysis and synthesis techniques have been used for many years in applied science and engineering. It is clear modern spectral analysis techniques will be able to solve even more sophisticated engineering and scientific problems in the future.

1.6 Conclusion

In Section 1.2, we first introduced the binary FSK communication system that appeared in the 1960s and then considered the M-ary FSK communication system, where the detection problem can be considered as a spectral analysis problem. In Section 1.3, the detection of a Doppler radar return waveform can be considered to be a spectral analysis problem [2]. In Section 1.4, frequency aspects of the human speech waveform were introduced [3]. In Section 1.5, various aspects of spectral analysis in physical problems were treated [4].

1.7 References

Some details on the M-FSK coherent and non-coherent modulation problems can be found in [1]. Various aspects of a Doppler radar system can be found in [2]. Details on the discussion of speech processing can be found in [3]. Various aspects of spectral analysis in physical problems are treated in [4].

[1] M. Schwartz, W.R. Bennett, and S. Stein, *Communication Systems and Techniques*, McGraw-Hill, 1966.
[2] G.W. Stimson, *Introduction to Airborne Radar*, Hughes Aircraft Company, 1983.
[3] A.S. Spanias, “Speech Coding: A Tutorial Review,” *Proceedings of the IEEE*, 1994, pp. 1541–1582.
[4] D.B. Percival and A.T. Walden, *Spectral Analysis for Physical Applications*, Cambridge University Press, 1993.

1.8 Exercises

1. Read the historical development of the Bell 101 and 203 modulations in Wikipedia.

2. If we just use the M-FSK modulation as considered in (1.2), the possible phase discontinuity when shifting from one frequency to another frequency can cause a large spectral sidelobe outside of the desired frequency band. Continuous-phase FSK has been introduced to mitigate this problem. See *Digital Communications*, 3rd edn., by J.G. Proakis, McGraw-Hill, 1995, Section 4.3.3, p. 190.
3. Read the history of Doppler radar in Wikipedia.
4. Read about the use of spectral analysis in speech processing in Wikipedia.