Avian Detection and Monitoring Using Frequency-stepped Chirp Signal Radar

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Abstract— The bird aircraft strike hazard (BASH) is a worldwide problem to aviation, which deprives lots of properties and lives every year. Avian radar systems are necessary to be developed for avian surveillance and early warning. In this paper, the frequency-stepped chirp signal radar is utilized to obtain high range resolution for micro-Doppler features extraction by means of synthetic bandwidth. The micro-Doppler features provide important information for avian detection and monitoring. The micro-Doppler effect in frequency-stepped chirp radar is analyzed in the paper and some micro-Doppler feature extraction methods are introduced.

1. INTRODUCTION

Along with the flourish of the aviation, the bird strikes are reported annually and the bird aircraft strike hazard (BASH) becomes a worldwide problem. Statistics suggested that about 10,000 bird strike accidents happened all around the world per year, and 90 percent occurred during take-off and landing in the vicinity of airports. It is necessary to develop avian radar system for avian detection and monitoring, which makes early warning be possible. Experiments illustrate that 3-centimeter wavelength surveillance radar (e.g., BIRDRAD) can detect the departure of migrants from different types of habitat within a range of 6 kilometers of the radar, and the Doppler weather surveillance radar (WSR-88D) can measure the density of birds in the radar beam as they begin a migratory movement within 60 kilometers [1], but trying to identify the type of bird is problematical. The abilities to distinguish the types of targets (birds, insects or aircraft with small size, such as Unmanned Aerial Vehicle), identity types of birds, and determine flock sizes are considered to be important goals for future research and development [2].

The radar imaging with high resolution is a potential technique to solve the problems. To explore the movement features of birds, the ultra-large-wideband signal is necessary to be utilized for high range resolution. In this paper, the frequency-stepped chirp signal \([3, 4]\) is applied to synthesize a signal with a bandwidth of 3 GHz for a range resolution of 5 cm. The range resolution is high enough to explore the micro-Doppler information of birds. The rotating structures in a radar target or mechanical vibrations of the target body may induce additional frequency modulation on returned signals and generate side-bands about the center frequency of the body Doppler frequency, called micro-Doppler effect [5]. Micro-Doppler feature can be regarded as an important signature of the target, and provides additional information for target detection, recognition and identification. The beating of bird’s wings can also cause micro-Doppler phenomenon, which offers a new approach to identify the birds: transmit frequency-stepped chirp signals to the birds, and then extract the micro-Doppler information from the echoes.

2. IMAGING PRINCIPLE OF FREQUENCY-STEPPED CHIRP SIGNAL

Frequency-stepped chirp signal is made up of a series of bursts, each of which consists of a sequence of chirp subpulses of stepped carrier frequency. The frequency variation in a burst is shown in Fig. 1. The \(i\)-th subpulse in a burst is written as (assume the initial time of the signal at \(-T_1/2\))

\[
U(t) = u_1(t - iT_r) \exp \left(j2\pi \left(f_0 + i\Delta f \right) t + \theta_i \right), \quad 0 \leq i \leq N - 1
\]

where \(u_1(t) = rect \left(t/T_1\right) \cdot \exp \left(j\pi\mu t^2\right)\) is the chirp subpulse, \(\mu\) is the frequency slope, \(T_1\) is the duration of the chirp subpulse, \(T_r\) is the subpulse repetition time, \(f_0 + i\Delta f\) is the carrier frequency of the \(i\)-th subpulse, \(\Delta f\) is the step size, \(\theta_i\) is the initial phase of the subpulse, and \(N\) is the number.
of subpulses in a burst. Assuming a target of a point-scatterer, the echo of the \( i \)-th subpulse from the target is

\[
S_i(t) = \text{rect} \left( \frac{t - iT_r - 2R/c}{T_1} \right) \cdot \exp \left( j\pi\mu(t - iT_r - 2R/c)^2 \right) \cdot \exp (j2\pi(f_0 + i\Delta f)(t - 2R/c + \theta_i))
\]  

(2)

where \( R \) is the distance between the target and the radar, \( c \) is the wave propagation velocity. The reference signal can be written as

\[
S_{\text{ref}}(t) = \text{rect} \left( \frac{t - iT_r - 2R_0/c}{T_{\text{ref}}} \right) \cdot \exp \left( j\pi\mu(t - iT_r - 2R_0/c)^2 \right) \cdot \exp (j2\pi(f_0 + i\Delta f)(t - 2R_0/c + \theta_i))
\]

(3)

where \( R_0 \) is the distance between the reference point and the radar, \( T_{\text{ref}} \) is the duration of the reference signal which is a little larger than \( T_1 \). After dechirping processing, it yields

\[
S_{ic}(t) = S_i(t)S_{\text{ref}}^*(t) = \text{rect} \left( \frac{t - iT_r - 2R/c}{T_1} \right) \cdot \exp \left( -j\frac{4\pi\mu}{c} \left( t - \frac{2R_0}{c} \right) R_{\Delta} \right)
\]

\[
\cdot \exp \left( -j\frac{4\pi}{c} (f_0 + i\Delta f) R_{\Delta} \right) \cdot \exp \left( j\frac{4\pi\mu}{c^2} R_{\Delta}^2 \right)
\]

(4)

where \( R_{\Delta} = R - R_0 \). Replace \((t - 2R_0/c)\) by \( t' \), then take the Fourier transform to Eq. (4) with respect to \( t' \) and remove the Residual Video Phase (RVP), it yields

\[
S_{ic}(\omega) = T_1 \text{sinc} \left( T_1 \left( \omega + \frac{4\pi\mu}{c} R_{\Delta} \right) \right) \cdot \exp \left( -j\frac{4\pi}{c} (f_0 + i\Delta f) R_{\Delta} \right)
\]

(5)

It can be found that the peak value of \(|S_{ic}(\omega)|\) appears at \( \omega = -4\pi\mu R_{\Delta}/c \), and in fact, it is the coarse range profile of the point-target created by the \( i \)-th subpulse exactly. \( N \) subpulses will create \( N \) coarse range profiles. Let \( \omega = -4\pi\mu R_{\Delta}/c \), and take Fourier transform of these coarse range profiles, it can be obtained

\[
S(k) = C \cdot \text{sinc} \left( k + 4\pi\Delta f R_{\Delta}/c \right) \cdot \exp \left( -j4\pi f_0 R_{\Delta}/c \right)
\]

(6)

where \( C \) is a constant. From Eq. (6) it can be found that the peak value of \( S(k) \) appears at \( k = -4\pi\Delta f \cdot R_{\Delta}/c \), therefore, the high-resolution range profile (HRRP) is obtained. Each burst creates a HRRP; by transmitting a number of bursts and taking the Fourier transform to the HRRPs with respect to slow-time, the ISAR image of the target can be obtained.

Generally, the size of bird is between 0.1m and several meters. To achieve the range resolution high enough to identify birds, we synthesize a signal with a bandwidth of 3GHz for a range resolution of 5cm.

![Figure 1: Frequency variety in a burst.](image1)

3. MICRO-DOPPLER EFFECT

If the target is a rigid body, after the motion compensation, the HRRPs obtained from each burst will be similar to each other. But in many cases, the radar target can’t be regarded as a rigid object, for example, the helicopter with rotating rotors and bird with wings beating. This kind of micro-motions may induce micro-Doppler effect, which provides abundant structure and motion information of the object for identification.

![Figure 2: The micro-motion of target.](image2)
As shown in Fig. 2, point $P$ is the reference point, $Q$ is a micro-motional point with velocity $v$ along the radar line of sight (LOS). The distance between $P$ and $Q$ at the initial time is $R_{\Delta 0}$. Because of the movement of $Q$, $R_\Delta$ in Eq. (4) should be expressed as follow:

$$R_\Delta = R_{\Delta 0} + iTrv$$ (7)

Generally, the displacement of $Q$ in a burst can’t exceed a coarse range cell. Eq. (5) can be rewritten as

$$S_{ic}(\omega) = T_1 \text{sinc} \left( T_1 (\omega + 4\pi \mu R_{\Delta 0}/c) \right) \cdot \exp \left( -j4\pi (f_0 + i\Delta f) \left( R_{\Delta 0} + iTrv \right)/c \right)$$ (8)

Thus, the HRRP peaks at

$$k = \Phi'(i) = -\frac{4\pi}{c} \Delta f \cdot R_{\Delta 0} - \frac{4\pi}{c} f_0 Trv - \frac{8\pi}{c} \Delta f iTrv$$ (9)

Observing Eq. (9), the first term denotes the initial location of the point $Q$, the second term demonstrates that the location of $Q$ has an offset proportional to $v$. Compared with the first and second terms, the last term of Eq. (9) is quite small and negligible, but this term may make the peaks of the HRRP expanded, especially serious when $v$ is quite large. Ignoring the last term, Eq. (9) is rewritten as

$$k = -\frac{4\pi}{c} f_0 Trv - \frac{4\pi}{c} \Delta f \cdot R_{\Delta 0}$$ (10)

It is obvious that the displacement of $Q$ in the HRRP $-4\pi f_0 Trv/c$ is proportional to its micro-motion velocity. Because the HRRP is obtained by N-point Fourier transform, the value range of $k$ is defined in $[-\pi, \pi]$. If $v$ is too large, $k$ in Eq. (9) may exceed this scope, and the peak of the HRRP may wrap and appear at the other side of the reference point. Assuming $f_0 = 94$ GHz, $R_{\Delta 0} = 0$, the absolute velocity $v$ must be smaller than about 20 m/s to avoid the wrapping phenomenon. As shown in Fig. 3(a) and Fig. 3(b), four points are all located at the reference point but with different velocities. We can see that the locations of them in the HRRP are related to their velocities. When the absolute value of $v$ varies from $8$ m/s to $25$ m/s, the location of according peak varies from the left side of the HRRP to the opposite side, and the peak becomes more and more expanded along with the increasing of $v$. According to the fact that the maximal velocity of bird’s beating is generally lower than 20 m/s, the wrapping phenomenon can be avoided.

![Figure 3: The micro-Doppler effect.](image)

Different micro-motions will cause different shapes of HRRPs, therefore, the spectrogram, which is defined as the module of the matrix having the HRRPs as vectors, includes the micro-motion information of the object. It provides a new approach to target identification. A bird model is shown in Fig. 4(a) and the spectrogram is shown in Fig. 4(b) when the flapping rate is 2 Hz.

4. EXTRACTION OF MICRO-DOPPLER INFORMATION

The micro-Doppler information contains the micro-motion information of the object, which is regarded as an important characteristic useful for target recognition. The extraction of the micro-Doppler information is an important work to achieve this goal.
As shown in Fig. 4(b), the spectrogram appears to be periodic due to the periodicity of the bird’s beating. That is to say, the period of the spectrogram is the same with the period of the bird’s beating. As is known, the larger is the size of the bird, the lower its flapping frequency is. Many birds with large size, such as glede and crane, even don’t beat their wings in a long time, but hover in the updraft for hours. Therefore, the frequency of the beating is important information to distinguish birds with different size, which can be obtained easily from the spectrogram using the image processing techniques such as autocorrelation.

The shape of the spectrogram also provides the characteristics of the bird’s motion useful for identification. The tiny difference of the movement manners can induce the difference in the spectrograms. Much more work has to do to make use of the shape characteristics because it is necessary to build a template database of all kind of birds for bird identification.

To explore the fine flying characteristic of the birds, many methods can be used, such as the time-frequency analysis and the Hough Transform. High-resolution time-frequency technique is considered as a nice modus for the extraction of micro-Doppler information and some references have taken profound discussions about it [5, 6]. The Hough Transform is utilized to extract the micro-motion characteristics of objects with rotating parts such as rotating frequency and radius in [7].

5. CONCLUSIONS

This paper proposes a new approach to the avian detection and identification for the prevention of bird strike in aviation. The frequency-stepped chirp signal radar is utilized to obtain the high range resolution for extraction of micro-Doppler features. The micro-Doppler features are very useful for bird identification. It has to be mentioned that we obtain the spectrogram based on the accurate motion compensation which is a difficult problem to resolve in the future work.

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