Frequency-domain Kirchhoff Migration for Near-field Radar Imaging

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***Abstract*—We present frequency-domain Kirchhoff migration, which is a fast and high-resolution imaging algorithm for ultra-wideband radar. The algorithm is developed by combining three conventional methods: Kirchhoff migration, frequency-wavenumber (F-K) migration, and inverse boundary scattering transform (IBST). Frequency-domain Kirchhoff migration is compared with conventional methods in terms of the computational load and resolution by applying the methods to measurements made for a handgun, which is an important target in various security-related applications including airport security.**

I. Introduction

Continuous effort has been made to develop a high-resolution imaging method using ultra-wideband radar [1], [2], [3], which is considered to be essential in many security-related applications including airport security systems for detecting concealed weapons. There are two conflicting demands for the radar imaging of concealed weapons: resolution and speed. High-resolution images provide detailed information of the concealed object, so that the object is more likely to be detected, while fast imaging computation is necessary to ensure passengers' convenience in many practical scenarios, such as airport safety inspection.

To improve resolution, Zhuge et al. [4] proposed modified Kirchhoff migration for a multiple-input and multiple-output array that can achieve high-resolution in near-field radar imaging. This algorithm was originally formulated in the time domain, leading to a heavy computational load. To improve computational speed, Zhang and Hoorfar [5] proposed the diffraction tomographic algorithm for radar imaging. Their algorithm produces an image using an integral with a specifically tailored kernel function that takes into account the propagation model. The advantage of this method is that the calculation is fast using the fast Fourier transform, because the integral is formulated in the frequency domain.

The present paper explains the principle of frequency-domain Kirchhoff migration [6], which is an extension of modified Kirchhoff migration [4] and formulated in the frequency domain. This method realized also by combining frequency–wavenumber (F-K) migration and the inverse boundary scattering transform (IBST) to enhance the processing speed. We apply frequency-domain Kirchhoff migration, together with delay-and-sum (DAS) migration, Kirchhoff migration, and F-K migration as conventional methods, to measurements for a handgun as the target and compare the performances of these methods in terms of the resolution and computational speed.

II. System Model

The assumed measurement system is a bistatic radar configuration with transmitting and receiving antennas, both positioned in the $z = 0$ plane. The midpoint between the transmitting and receiving antennas is denoted $(X, Y, 0)$, and the separation between the antennas is $2d$. The transmitter and receiver are therefore located at $\boldsymbol{r}_1 = (X - d, Y, 0)$ and $\boldsymbol{r}_2 = (X + d, Y, 0)$, respectively. With the antenna pair scanning at discrete intervals across a region of the $z = 0$ plane, signals are transmitted and echoes are received. For the antennae midpoint $(X, Y, 0)$, the recorded signal is labeled $s(X, Y, Z)$, where $Z = ct/2$. Here, c is the speed of light and t is time.

III. Frequency-domain Kirchhoff Migration

This section provides an overview of the procedures of frequency-domain Kirchhoff migration, the details of which are found in [6]. First, an approximate target image is calculated using the texture angle method [7] and the IBST [8], [9], [10], [11], [12]. Although the image generated using the IBST is not accurate, the approximate positions of scattering centers are obtained. Because the approximate position of the target determines the integrand of the Kirchhoff integral [4], we can calculate the approximate Kirchhoff integrand using the texture angle method and IBST. This integrand is a function of time and the antenna position, and called the modified Kirchhoff signal.

Next, the time-domain calculation of the Kirchhoff integral is replaced by F-K migration, which means that the modified Kirchhoff signal is transformed to the F-K domain using the fast Fourier transform, and the final image is obtained through a change of variables, multiplication of the Jacobian determinant, and application of the inverse fast Fourier transform. This method combines fast IBST processing with F-K migration to obtain a high-resolution image within a short time. The performance of the method is compared with performances of conventional methods in the following section.

Fig. 1. Handgun target used in the measurement.

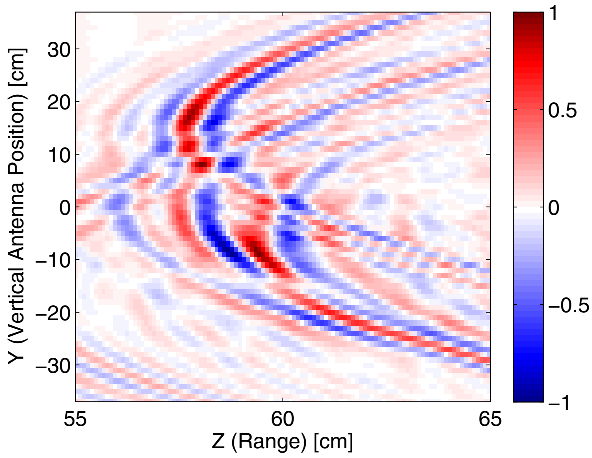

Fig. 2. Original measured signal.

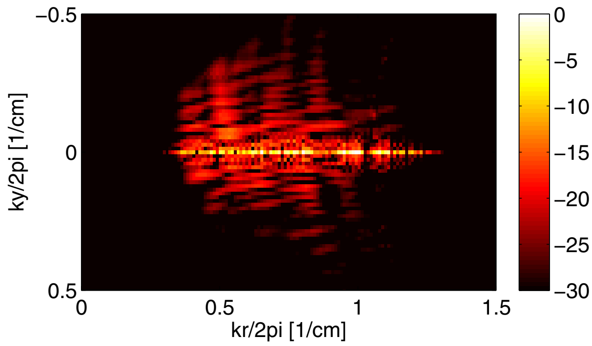

Fig. 3. Frequency–wavenumber spectrum of the conventional F-K migration (in decibels).

IV. Performance Evaluation through Measurement

In this section, to evaluate the performances of DAS migration, Kirchhoff migration, F-K migration and the proposed method, we apply the methods to radar measurements of a handgun as a target (see Fig. 1). The datasets were measured in the frequency domain using a network analyzer (PNA E8364B, Agilent Technologies) sweeping 161 points at frequencies from 4.0 to 20.0 GHz. Two Vivaldi antennas were used with $2d = 5.5$ cm antenna separation. The pair of antennas scan in the X-Y plane ($Z = 0$) in the range $X_{\min} \leq X \leq X_{\max}$ and $Y_{\min} \leq Y \leq Y_{\max}$ at intervals of $\Delta_{X,Y}$, where $\Delta_{X,Y} = 1.0$ cm and $X_{\min}, X_{\max}, Y_{\min}$ and $Y_{\max}$ are –37.0, 37.0, –37.0 and 37.0 cm, respectively. Thus, the total number of measurement points is $75 \times 75 = 5625$.

Figure 2 shows a section ($X = 18$ cm) of the signals received in the measurement. This signal is transformed in to the F-K domain as shown in Fig. 3, where the horizontal and vertical axes respectively correspond to the radial wavenumber and y-component of the wavenumber. Figure 4 shows the image produced using the texture angle method and IBST. Although this image is not very accurate, the approximate image shape is obtained.

Using the approximate IBST image, the original signal can be modified according to the Kirchhoff integrand, which is calculated as shown in Fig. 5. Higher-frequency components of the signals are emphasized in the figure, when compared with Fig. 2. This modified Kirchhoff signal is transformed to the F-K domain in Fig. 6. In this figure, the higher wavenumber component is clearly enhanced compared with the case in Fig. 3.

The images obtained using DAS migration, Kirchhoff migration, F-K migration, and the proposed method are shown in Figs. 7–10. The time-domain methods (DAS migration and Kirchhoff migration) are time consuming and impractical in many security-related applications, whereas the frequency-domain methods (F-K migration and the proposed method) are fast and promising in such applications. With regard to the resolution, the image of Kirchhoff migration (Fig. 8) has higher resolution than that of DAS migration (Fig. 7). Similarly, the image of the proposed method (Fig. 10) has higher resolution than that of F-K migration (Fig. 9).

The computational times were 1119, 1149, 2.5, and 4.5 s for DAS migration, Kirchhoff migration, F-K migration and the proposed method, respectively. Note that the computational times were measured using codes implemented in C language on a computer with an Intel Xeon E5-2650 v2 processor and 32 GB of RAM. We conclude from these results that the proposed method achieves fast processing and high-resolution imaging simultaneously, and is thus a promising method for real-time security imaging systems.

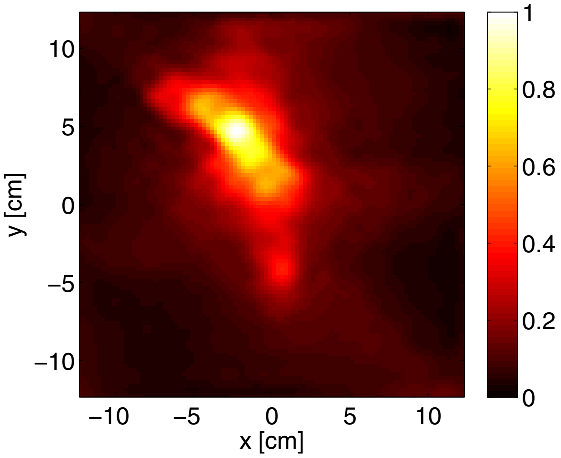

Fig. 4. Radar image generated using the texture angle method and IBST.

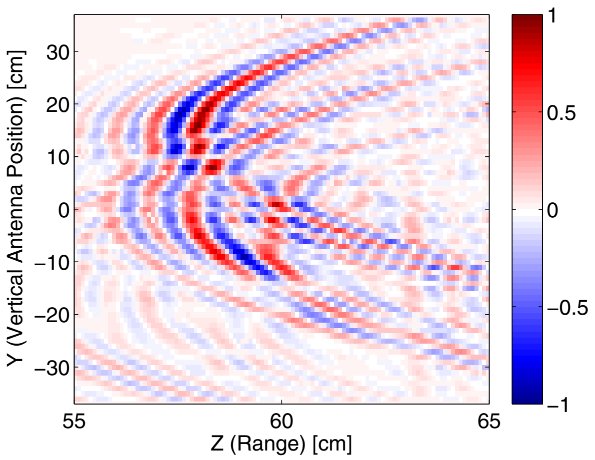

Fig. 5. Modified Kirchhoff signal generated using frequency-domain Kirchhoff migration.

V. Conclusion

This paper presented frequency-domain Kirchhoff migration, which is a combination of four techniques: Kirchhoff migration, F-K migration, the texture angle method, and IBST. The proposed method was applied to a data set measured for a handgun as a target. The results indicated that the proposed method provides high resolution, while it has high processing speed because it is implemented in the frequency domain.

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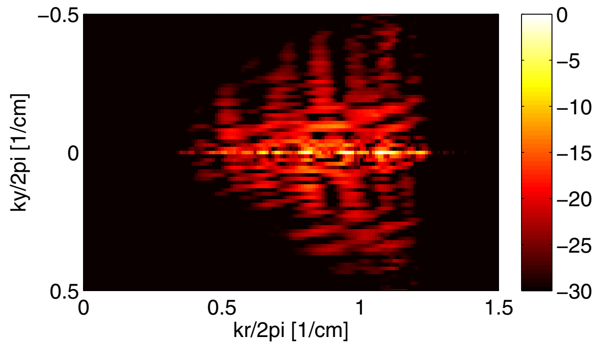

Fig. 6. Frequency–wavenumber spectrum of the frequency–domain Kirchhoff migration (in decibels). High frequency–wavenumber components are enhanced.

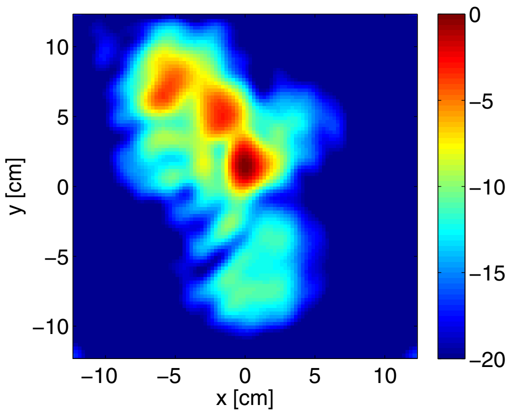

Fig. 7. Radar image generated using conventional DAS migration. The computational time was 1119 s.

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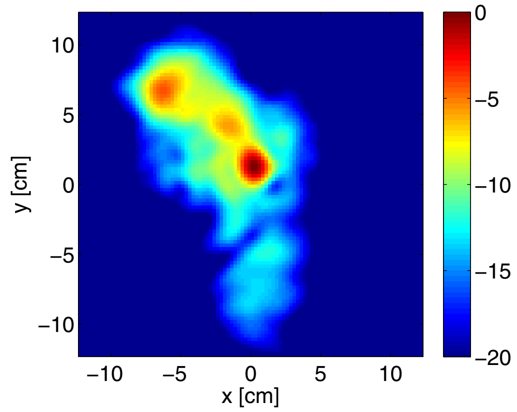

Fig. 8. Radar image generated using modified Kirchhoff migration [4]. The computational time was 1149 s.

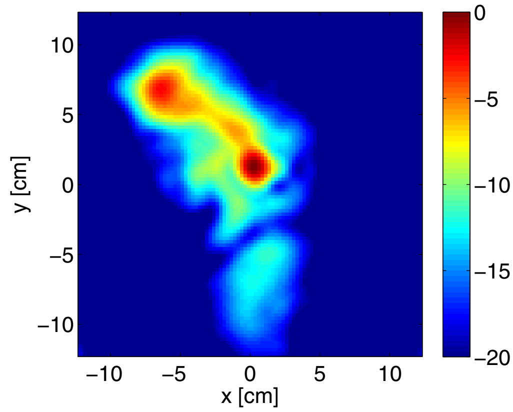

Fig. 10. Radar image generated using the proposed method (frequency-domain Kirchhoff migration) [6]. The computational time was 4.5 s.

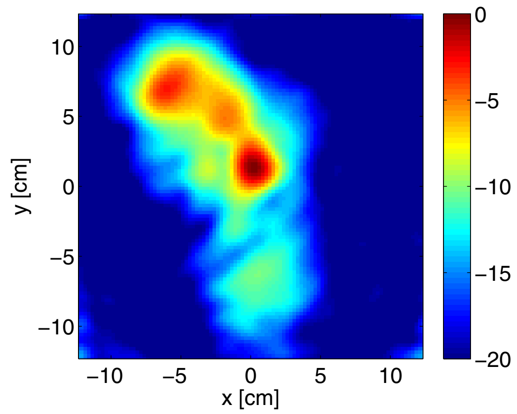

Fig. 9. Radar image generated using conventional F-K migration. The computational time was 2.5 s.

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