3-Dimension Imaging System of Burden Surface with 6-radars Array in a Blast Furnace

Xianzhong CHEN,1,2) Jidong WEI,1,2)* Ding XU,3) Qingwen HOU1,2) and Zhenlong BAI1,2)

1) School of Automation & Electrical Engineering, University of Science and Technology Beijing, Beijing, 100083 China. 2) Key Laboratory of Advanced Control of Iron and Steel Process (Ministry of Education), University of Science and Technology Beijing, Beijing, 100083 China. 3) EM Lab, Beijing University of Aeronautics & Astronautics, Beijing, 100191 China.

(Received on May 11, 2012; accepted on June 26, 2012)

Harsh environment in Blast Furnace (BF) poses a big challenge for metallurgical industrial radar measurement of burden surface for ore and coke. The improved signal processing algorithm enhances the real-time performance. Antenna is specially designed for continuous stable signal acquirement, high temperature resistance and anti-dust ability. The experiment results illustrate that the single radar meets the accuracy requirement of solid bulk material. A new BF Burden Surface Measuring System is developed for real-time BF 3-D imaging. Distributed 6-radars array mounted on the top of 2500 m³ BF. A virtual 3-D imaging is achieved with a reconstruction algorithm of 6-radars array according to the actual shape of BF. 3-D imaging system with 6-radars array provides an improved technique for intelligent control of burden distribution during BF iron making process.

KEY WORDS: radar; 6-radars array; BF; burden surface; 3-D imaging.

1. Introduction

Blast furnace (BF) is a large-scale, high temperature, high pressure and high dust enclosed reactor, with 300–500°C on the top of BF, with 10–100 m/s gas flow, 200–300 g/m³ dust concentrations. The burden surface, which is composed of many layers of ore and coke (see Fig. 1), is controlled by tilting shoot angles of the charging chute. Burden surface measurement1) plays an important role on BF iron making. It has large effect on not only the production of pig iron, but also the stability of BF iron making.

There are different BF monitoring methods to gather data of burden distribution. Temperature field distribution measurement, Infrared imaging and level detection are three kinds of approaches. Temperature filed distribution, measured by crossing temperature from the throat of BF, indirectly reflects burden distribution.2) Infrared imaging3–5) presents a method of high reliability and easy maintenance for direct observation inside BF. But it cannot get distance information. Detail technique which is applied in level detection mainly contains mechanical device, laser and microwave. The mechanical device (MD) rewinds steel rope until the heavy hammer meets the burden surface. The length of rope is the height of burden surface. Direct measurement ensures the correctness and precision. Weakness of MD method is discontinuity. Laser scanner system6,7) has high data acquisition rate and large measurement range. Laser also has high resolution and accurate positioning. But wave length limits penetrability of laser in BF dust environment. SIEMESE LR series are 24 GHz FMCW radar level transmitters. They feature self-learning algorithm with TVT shape. But they require improvement on bulk solid in BF environment. The planar patch antenna array,8,9) which was made by Emil Nilson in Sweden, mounted on a running industrial BF. It faced a system breakdown shortly cause of the effect of high temperature for the patch antenna.

This paper presents a metallurgical 6-radars array which is designed for application of BF with extreme working conditions and harsh environment. The remainder of this paper is organized as follows: Section 2 introduces system hardware and software design. In order to improve stability and accuracy, signal processing algorithm is utilized to integrate 6 radars to form sensors array. Experimental procedure is

* Corresponding author: E-mail: cxz@ustb.edu.cn
DOI: http://dx.doi.org/10.2355/isijinternational.52.2048
illustrated in Section 3, including laboratory, pilot plant and iron making BF. Finally, conclusions are discussed in Section 4.

2. Industrial Radar Design

2.1. Antenna with High Temperature Resistance and Anti-dust Ability

Horn antenna with 24–26 GHz is adopted. According to the simulated HPBW (Half Power Beam Width, see Fig. 2), 8 degree aperture angle is available and the horn diameter is 110 mm, producing 10 degree beam-width.

The antenna waveguide contains PTFE ($\varepsilon_r = 2.08$) dielectric rod to against BF dust. Tapered triangle transition structure of the rod has been experimentally determined through the S11 analysis (see Figs. 3, 4). The beam width is about 10°, side lobe level is less than 20dB over entire frequency band.

The cooling and anti-adhesion design (see Fig. 5) in radar antenna plays an important role in BF production with 300–500°C. The length of radar insulation sleeve with upper radiator is adjustable. Figure 5 shows the process of rotational purging gas. There are two layers of small holes in the cavity inner wall, the upper layer locate in the PTFE rod tip. Gas such as N2 blow into the cavity at an oblique angle, and two layers of homonymous rotating purging airflow are formed to prevent dust and tar adhesion at varied temperature and humidity environment.

2.2. The Measurement Principle of SFCW

SFCW radar\textsuperscript{11,12} applies stepped sweep of bandwidth (1.66 GHz) to emission signal. Total signal processing time cost contains 2 parts: sampling time cost and FFT time cost. Simulation (see Table 1) shows that sampling time cost is 94% of total. So shorten sampling length can reduce total time cost. The emission signal frequency $f$ can be expressed by:

$$f = f_0 + \frac{B}{N} \times \Delta f_i \quad i = 0, 1, \cdots N - 1 \quad (1)$$

Where $B$: FM bandwidth; $f_0$: initial frequency; $f$: emission signal frequency; $N$: the number of sample point; $\Delta f_i$: frequency resolution.

Substitute Eq. (1) to FMCW echo signal Eq. (8), low frequency can be expressed by

![Fig. 2. The HPBW at 24 GHz (CST simulation). (a) XOZ plane (b) YOZ plane.](image)

![Fig. 3. Simulated $S_{11}$ versus different PTFE end-fire structure. (h: the height of PTFE rod end, millimeter).](image)

![Fig. 6. Mean-shift process for stabilizing distance measurement tendency (The green line is tendency with spectrum average method. The detail is not mentioned as its bad stability performance).](image)

![Fig. 14. Accuracy comparison of coke stack level detection with different angle and different surface roughness.](image)
\[ s(t) = V \times \cos(2\pi \frac{2R}{C} \times \Delta f \times f_i + \Phi_o) \] ........... (2)

According to the relationship between frequency spectrum and distance,\(^\text{11)}\) echo signal frequency is
\[ f = \frac{i}{N \times f_s} \times \frac{2R}{C} \times \Delta f \times f_s \] ............. (3)

So distance \( R \) is
\[ R = \frac{i}{N} \times \frac{C}{2N\Delta f} \] ............... (4)

Where \( C \): velocity of light, \( 3 \times 10^8 \) m/s; \( f_s \): sample frequency.

According to Eq. (4), the range resolution is
\[ \Delta R = \frac{C}{2N\Delta f} \] .................................. (5)

According to Eq. (5), range resolution is certain as \( N\Delta f = B \). We can adjust the allocation of \( N, \Delta f \) to balance the real-time performance of algorithm processing with TI DSP 28335 chip. According to Table 1, the shorter sampling length was, the shorter total time consume. As 1024 sampling length was chosen in the imaging system, the TMS320F28335 is 150 MHz (6.67 ns cycle time), 7 168 333 DSP instruction cycles means 47.812 ms. So the real-time performance of single radar satisfies the requirement of BF imaging.

2.3. Intelligent Signal Processing Algorithms

Normally, the measurement of a bulk solid material, for example ore or coke, will face the problem of fluctuation of value even it’s in the same conditions, besides the producing process. We adopt a mean-shift and adaptive threshold method to prevent frequency spectrum catastrophe, also same parameters are carefully chosen to reduce signal interference according to the actual BF situation.\(^\text{13,14)}\)

2.3.1. Mean-shift Method

Metallurgical process is an orderly, but noisy, time series process. Exponential smoothing method can be used with discrete set of repeated measurements. The mean-shift method is derived from Exponential smoothing method. In order to reduce the impact of sharp distance change, we calculate the distance using mean-shift processing of the continuous FFT frequency spectrum, the formula is as follows:
\[ f_{\text{acc}}(i) = (1-\alpha) f_{\text{acc}}(i) + \alpha f(i) \] ............... (6)

Table 1. Time consuming comparison of different sampling lengths (1 DSP instruction cycle = 0.667*10^{-8} second).

| Sampling length | Time/DSP instruction cycle |
|-----------------|-----------------------------|
|                 | Sampling | FFT | Total |
| 256             | 1 759 771 | 98 117 | 1 857 888 |
| 512             | 3 519 515 | 108 505 | 3 628 020 |
| 1 024           | 7 039 003 | 129 330 | 7 168 333 |

Fig. 4. 2-Dimensional radiation pattern of the horn antenna at 24 GHz. (a) XOZ plane (b) YOZ plane.

Fig. 5. Industrial radar antenna. (a) structure design (b) radar in lab (c) radar on top of BF 1. Radar adjustable insulation sleeve. 2. Gas hole. 3. Flange. 4. Gas cavity. 5. Antenna horn. 6. PTFE dielectric rod.
Where \( \alpha \): mean-shift coefficient, \( 0 \leq \alpha \leq 1 \); \( f(i) \): distance value at time \( i \); \( facc(i) \): mean-shift distance value at time \( i \).

The smaller the value of \( \alpha \), the greater prior \( f \) influence on the result, and vice versa.

The mean-shift method can effectively inhibit the random fluctuation (see Fig. 6) which is caused by the unstable gas flow floating in the burden surface and the up and down tendency corresponding with the phenomenon of metallurgical process.

2.3.2. Adaptive Threshold Method

Each point value of adaptive threshold is the weighted average of the corresponding point and around \( n \) points in the frequency spectrum. The adaptive threshold line \( s(i) \) is:

\[
s(i)=\alpha_1 f\left(\frac{i-n}{2}\right)+\alpha_2 f\left(\frac{i-n+1}{2}\right)+\cdots+\alpha_n f\left(\frac{i+n}{2}\right)+b+\alpha_{n+1}\]
\[
\text{.......................... (7)}
\]

Where \( \alpha_1,\alpha_2,\cdots,\alpha_n,\alpha_{n+1} = 1 \) is chosen according to the radar waveform characteristics and the actual needs.

The adaptive threshold line (see Fig. 7) increases the reliability of signal processing and distinguishes signal from noise.

2.4. Radar Sensor Circuit and Communication with Host Computer

Radar circuit design includes: HF module, signal conditioning circuit and DSP module.

2.4.1. HF Module

HF module (23.0–24.6 GHz) contains the crystal oscillator (12 MHz) as the PLL reference frequency input, digital phase detector (ADF4107), OP27G and the VCO (H515). The HF module gets the required 23.0–24.6 GHz microwave signal by the frequency multiplier (H576). Received signal and local oscillator signal are mixed in the passive integrated mixer HMC292. Low-pass filter removes high frequency components of the beat signal. Then output is the intermediate frequency component which reflects the burden surface profile.

2.4.2. Signal Conditioning Circuit

Signal conditioning circuit contains signal amplification, filter and bias circuit. The signal (frequency between 1.5–3.6 KHz) is converted to 0–3 V DC voltage output by the internal DSP AD sampling. Environmental noise which mainly contains low frequency component can be reduced by high-pass filter. Experimental results denote that bandpass filter can increase SNR from –5 dB to 24.7 dB.

2.4.3. Digital Signal Processing Module

The Ti DSP28335 and ADF4107 McBSP interface communication are adopted. SN65HVD230 is also adopted as CAN transceiver whose transmission rate is 20 Kbps or 80 Kbps.

2.5. Calculated Position to Form a 6-radars Array

Radars distribution strategy (see Fig. 9) ensure that minimum radar obtain maximum information. According to the effective cover area of single radar on BF burden surface, the minimum quantity of radars can be calculated. Radar launch angle is \( \alpha \) and the vertical installation height is \( z \) meters.

The antenna design (section 2.1) \( \alpha = 8^\circ \) and installation height \( z = 4.7 \) m. So the diameter of single point radar effective cover area is 6.7 meters. As the radius of the burden surface of 2 500 m \(^3\) BF is 4.1 meters, the quantity of radars along the radius direction should be no less than 6.

To make the data accurate and get the key point messages, the position of 6-radars array (see Fig. 10) is calculated and optimized along the radius direction. Due to field position limitation some radars can’t be installed vertically.

2.6. Imaging Algorithm

The BF charging principle illustrates that the trajectories of rotating chute almost produce annular burden surface distribution. A surface reconstruction algorithm of mathematical model is generated according to the position of 6-radars array and the BF charging principle.

Step 1. Convert hypotenuse distance to vertical distance.

According to installation parameter (see Table 2), oblique radar distance needs to be converted to vertical distance.
The vertical distance $\ell_v$ can be expressed by

$$\ell_v = \ell_d \times \cos \alpha$$ .......................... (8)

Where $\ell_d$: distance value measured by radar; $\alpha$: projection angle.

Step 2. Make least-squares parametrization.

A parametric surface$^{[5]}$ can be written in the form

$$z = f(x, y) = a_1 + a_2 x + a_3 y + a_4 x^2 + a_5 xy + a_6 y^2 + a_7 x^3 + a_8 x^2 y + a_9 xy^2 + a_{10} y^3$$ .......................... (9)

Least-squares parametrization method is chosen to obtain basis coefficient. Let $[h_1(l_i), h_2(l_i), h_3(l_i), \cdots, h_6(l_i)]$, with $l_i = (x_i, y_i)$ and $h_j(l_i) = l_i^n y_i^j$, denote exponent basis in Eq. (9). Then we can get

$$f(l_i) = \sum_{j=1}^{6} a_j h_j(l_i)$$ .......................... (10)

By considering the node set $(X, Y) = \{(x_i, y_i) \in R^2 : i = 1, \cdots, n\}$ Eq. (10) is equivalent to matrix equations

$$Z = HA$$

Here $A$ and $Z$ are the column vectors $(a_1, a_2, \cdots, a_6)^T$ and $(z_1, z_2, \cdots, z_6)^T$ respectively. The matrix $H$ is $n \times n$

$$\begin{pmatrix}
  h_1(l_1) & \cdots & h_6(l_1) \\
  \vdots & \ddots & \vdots \\
  h_1(l_n) & \cdots & h_6(l_n)
\end{pmatrix}$$

If $n$ is less than radar quantity, $A$ has a unique solution.

Least-squares parametrization method$^{[5]}$ satisfies $E(f) = \sum_{j=1}^{n} \left( f(l_j) - z_j \right)^2 = \sum_{j=1}^{n} \left( \sum_{i=1}^{6} a_i h_i(l_j) - z_j \right)^2$. It has a global minimum which is attained when $\frac{\partial E}{\partial a_i} = 0$ for all $i$.

So we get

$$\frac{\partial E}{\partial a_i} = \sum_{j=1}^{n} \left( 2 \left[ f(l_j) - z_j \right] \frac{\partial f(l_j)}{\partial a_i} \right) = 2 \sum_{j=1}^{n} \left( h_i(l_j) \frac{\partial f(l_j)}{\partial a_i} - z_j \frac{\partial h_i}{\partial a_i} \right)$$

$$= 2 \sum_{j=1}^{n} \left( h_i(l_j) \frac{\partial f(l_j)}{\partial a_i} - z_j \frac{\partial h_i(l_j)}{\partial a_i} \right)$$

$$= 2 a_i \sum_{j=1}^{n} \left( h_i(l_j) h_i(l_j) + \cdots + h_i(l_j) h_i(l_j) \right)$$

$$= a_i \sum_{j=1}^{n} \left( h_i(l_j) h_i(l_j) + \cdots + h_i(l_j) h_i(l_j) \right)$$

$$= 0$$

It is equivalent to n x n matrix equations when $i = 1, 2, \cdots, n$

$$\begin{pmatrix}
  a_1 \sum_{j=1}^{n} \left( h_1(l_j) h_1(l_j) \right) + a_2 \sum_{j=1}^{n} \left( h_1(l_j) h_2(l_j) \right) + \cdots + a_6 \sum_{j=1}^{n} \left( h_1(l_j) h_6(l_j) \right) = \sum_{j=1}^{n} \left( z_1 h_1(l_j) \right) \\
  a_1 \sum_{j=1}^{n} \left( h_2(l_j) h_1(l_j) \right) + a_2 \sum_{j=1}^{n} \left( h_2(l_j) h_2(l_j) \right) + \cdots + a_6 \sum_{j=1}^{n} \left( h_2(l_j) h_6(l_j) \right) = \sum_{j=1}^{n} \left( z_2 h_2(l_j) \right) \\
  \vdots \\
  a_1 \sum_{j=1}^{n} \left( h_6(l_j) h_1(l_j) \right) + a_2 \sum_{j=1}^{n} \left( h_6(l_j) h_2(l_j) \right) + \cdots + a_6 \sum_{j=1}^{n} \left( h_6(l_j) h_6(l_j) \right) = \sum_{j=1}^{n} \left( z_6 h_6(l_j) \right)
\end{pmatrix}$$
As Step 1 and Table 2 give us \((x_i, y_i, z_i)\) for \(i = 1, 2, \ldots, 6\), we can get basis coefficient \(A\).

Step 3. Interpolate with least-squares parametrization.

Node set interpolation can generate a parametric surface (see Lofting Surface in Fig. 17). The reconstruction process is done under boundary conditions which are derived from expert experience model. The model shows that concave exists at center and edge areas due to temperature distribution.\(^2\)

3. Experimental Results

3.1. Radar Level Detection

3.1.1. Radar Stability Test in Laboratory

Distance measurement between single radar and a fixed target (smooth iron plate) was done in laboratory environment (see Figs. 11, 12). Due to the improvement of SFCW

Fig. 11. Single radar stability test in laboratory. (a) scenarios (b) radar hardware.

Fig. 12. Stability of radar in laboratory (Laser distance is 5.414 m).

Fig. 13. Accuracy test in pilot plant. (a) scenarios (b) coke particle size.

Fig. 15. Industrial radar test in the process of iron making.
3.2. 6-radars Array Imaging

Six radars form 6-radars array with calculated position and algorithm. The 6-radars array monitoring system (see Fig. 17) keeps running in Baosteel Co. Ltd (Shanghai, China) for 4 years. The burden level tendency of imaging system keeps consistent with actual situation. The 3-D imaging with actual data from 6-radars array indeed reflects the tendency and spatial distribution characteristic of burden surface in BF iron making process.

4. Conclusions

A BF Burden Surface Imaging System is developed in this study. The system contains industrial 6-radars array and signal processing algorithm. The cooling and anti-adhesion design of radar antenna prolongs maintenance cycle. The improved SFCW and signal processing algorithm ensure stability and accuracy. The performance test in lab, pilot plant and industrial field illustrate that fixed position of radars and 3D imaging algorithm meet the auto control demand of BF iron making.

It is proved that burden surface could be reconstructed by 3-D Imaging System in hash environment with compute. Constantly running since 2007 in Baosteel Co. Ltd illustrates that 3-D imaging system indeed reflects the tendency and distribution characteristic of burden surface during BF iron making. The system can be used to optimize industrial control of BF iron making.

Acknowledgements

This project is supported by National High technology Plan (2006AA04Z177), Metallurgical Engineering Research Institute basic theory research of USTB (YJZ2010-009) and Baosteel Innovation Funding. We also thank Wu Yun for designing the 3D imaging software and Chu Bin from Baosteel Co. Ltd (Shanghai,China) for giving the access to the metallurgical data of 2,500 m³ BF for modeling and simulations.

REFERENCES

1) J. Liu, X. Chen and Z. Zhang: Meas. Sci. Technol., 17 (2006), 135.
2) L. Zhentao, W. Min, C. Weihua and H. Yong: Control Conf., 2008, CCC2008. 27th Chinese, IEEE, Piscataway, NJ, (2008), 285.
3) M. Birk, O. Marklund and A. Medvedev: Industry Applications Conf., 2001. Thirty-Sixth IAS Annual Meeting, IEEE, Piscataway, NJ, (2001), 1354.
4) R. Usamentiaga, L. Perez, J. Molleda, D. Garcia and S. Huerta: Instrumentation and Measurement Technology Conf. (I2MTC), IEEE, Piscataway, NJ, (2011), 1.
5) G. Zhengkai, X. Jingyi and C. Zhangning: Iron Steel, 37 (2002), 8.
6) S. Guo and Y. Sun: E-Product, E-Service and E-Entertainment (ICEEE), 2010 Int. Conf., IEEE, Piscataway, NJ, (2010), 1.
7) S.-K. Kuo, W.-C. Lee and S.-W. Du: ISIJ Int., 48 (2008), 1354.
8) E. Nilsson and L. Baath: IEEE Sens. J., 7 (2007), 1025.
9) E. Nilsson: Sensor Platform for 3D Microwave Interferometry Imaging, Theory and Experiments, Chalmers University of Technology, Goteborg, (2006).
10) X. Chen, F. Liu, Q. Hou and Y. Lu: Electronic Measurement Instruments, ICEMI ‘09, 9th Int. Conf., IEEE, Piscataway, NJ, (2009), 1.
11) C. Xianzhong, M. Liangliang and H. Qingwen: ICSPS 2010, 2nd Int. Conf., IEEE, Piscataway, NJ, (2010), V3-181.
12) A. Gurbaz, J. McClellan and W. Scott: IEEE SIGNAL, 57 (2009), 2640.
13) J. Xin and A. Sano: IEEE SIGNAL, 53 (2005), 4485.
14) M. Fashing and C. Tomasi: IEEE PATT A, 27 (2005), 471.
15) M. S. Floater: CAGD, 14 (1997), 231.