Real-time Meniscus Level and Slag Thickness Measurement by RADAR

Part I: System Design and Characterisation

Frenk van den Berg and Haibing Yang
Tata Steel Research, Development and Technology, 1970 CA, IJmuiden, The Netherlands

ABSTRACT

The cleanliness of steel is determined by the entrapment rate of liquid slag at the meniscus during continuous casting. The entrapment rate is minimal when the meniscus level is stable. Common methods to study the meniscus level stability have limitations in either measurement rate, capability to distinguish between slag and liquid steel, lateral resolution and freedom of measurement location.

To overcome these limitations, we have developed, in collaboration with the Dutch Institute for Defense, Security and Safety, an ultra-wideband RADAR system as prototype for highly resolved studies in monitoring slag thickness and meniscus level. Due to the unprecedented extreme ultra-wideband feature (bandwidth = 35 GHz), sub-mm distance resolution can be obtained with this system, with measurement rates up to 10 times per second.

Part I of this contribution describes the features and performance of the system. Part II will cover results of trials on liquid steel confirming the fine resolution of the system and data on the evolution of the slag thickness in time during heating.

Introduction

In the process chain involved in steel manufacturing, continuous casting of liquid steel is an important step to produce high quality solidified slabs, with typical dimensions of 12m length, 2m width and 0.12m thickness, thus weighing about 20 ton each. These slabs constitute the input for the subsequent process step, i.e. hot rolling. In the casting process, liquid steel is poured from ladles (containing 300 tons liquid steel) into a water-cooled copper mould via a ceramic nozzle, see Figure 1. The mould has a curved shape, starting vertically for liquid steel supply, and, after a quarter circle with radius of about 12 m, ending horizontally, where the infinite strand is cut into pieces (slabs) of about 12 m length. Every 4 minutes, such a slab is produced at the steel plant in IJmuiden.

For appropriate process control, the level of the liquid steel (i.e. meniscus) in the mould is measured. Commonly used level measuring methods include eddy current based techniques, and measurements based on the absorption of radioactive gamma rays [1-4]. These techniques are mostly spot measurements with relatively long integration time (seconds). However, the meniscus is generally not flat as standing or running waves can occur. Evidently, in this case, a (slow) spot measurement gives limited information. This explains the need for an improved measurement technique, which provides, besides the mean level of the liquid steel, also information on its height profile over the width as well as indication of the dynamics of the meniscus.

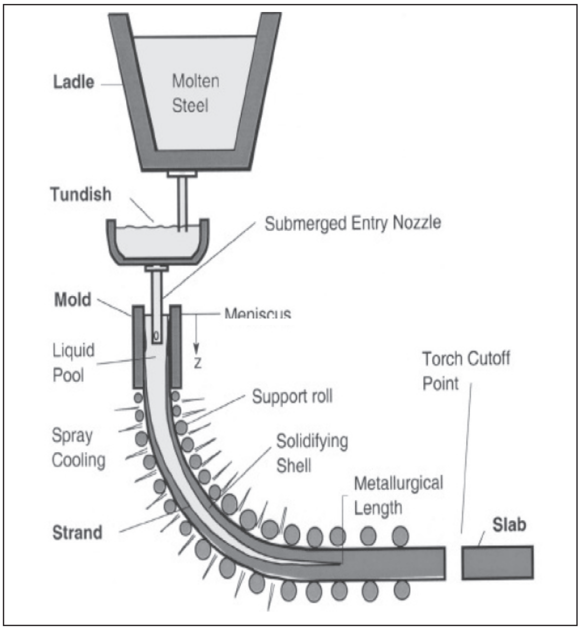

Fig. 1: Continuous casting process.

The business motivation for such a time-resolved meniscus height profile measurement is that it enables a dynamic adaptation of the casting speed, resulting in elevation of the average casting speed, thus capacity increase of the plant. Moreover, improved control over the meniscus stability will enhance the steel cleanliness, which constitutes an important quality factor of the product.

The local conditions at the caster constitute complicating factors for the measurement. For instance, a layer of mould powder/slag with unknown thickness (thickness range = 20 - 120 mm) floats on top of the meniscus. The measurement device has to "look through" this layer. An additional condition is the high temperature of around 1550°C of the liquid steel surface to be probed. As the measurement equipment may be positioned 0.3-0.5m above the surface, cooling is reckoned well possible, especially taking into account the attenuation of the heat radiation by the mould powder/slag layer. Because of the aforementioned measurement conditions, optical methods are not suitable for meniscus level monitoring.

A promising technique to this aim is RADAR. RADAR level measurements are already commonly applied in process industries for measuring liquid levels in storage tanks and reactor vessels. The principle behind the radar level measurement is either a Time-Of-Flight (TOF) method, a Frequency Modulated Continuous Wave (FMCW) method [5] or a phase-modulated method, called Radio-Wave Interferometry (RWI). In TOF, the (very small) time delay between emission and receipt of the radiofrequency (RF) pulse is determined, from which the distance is calculated. Due to the difficulty of very accurate timing (the time resolution is at best ~ 0.1ns), the height (or distance) resolution is limited to 1cm or worse. In FMCW radar, the frequency of the emitted RF signal is swept in a saw-tooth pattern, and the emitted signal is mixed with the received signal. Due to the frequency sweep, the received signal has a somewhat lower frequency than the actually emitted signal. The difference frequency, obtained by the mixing, gives a measure of the distance. Since frequencies can be determined with high accuracy, the distance resolution depends solely on the bandwidth of the frequency sweep. In RWI, the same principle is followed as in FMCW, but with phase modulation rather than frequency modulation. However, for a single frequency, the distance obtained still has the uncertainty of $n*\lambda$, n being a positive integer and λ the wavelength. Hence, the absolute distance is obtained by solving the equations for a multitude of frequencies.

Within steelmaking and casting, Malmberg et al [6-8] studied radar dielectric properties of synthetic and industrial slags like EAF-slag (from the Electric Arc Furnace), converter slag (or "LD-slag"), and ladle slag, using a broadband antenna horn with frequency range 2-18 GHz and a phase modulation method. Main application was the (slag) level detection during the EAF and converter processes. Disadvantage of their broadband antenna horn technique is the loss of lateral resolution as the beam is divergent and the fact that an intrinsic nuisance of horn antennas is that the phase centre varies with the frequency.

Advantage of the radar techniques is that they can be engineered to have an imaging capability. This would allow a measurement providing the required lateral resolved information to sample the meniscus profile. Secondly, radar methods have intrinsically low integration times, so that they can provide the meniscus profile data multiple times per second. As such, radar technology is a powerful candidate to improve on the current sensing possibilities in the mould. The challenge is to develop a radar system having high directionality combined with a high distance resolution. In this paper, an ultra-wideband radar system is presented which is used to study the feasibility of a real-time meniscus level measurement. By this system, both high directionality and resolution can be achieved.

This paper is organized as follows. The realisation of the system and its characterisation are reported in Section 2 and 3, respectively. Part II describes the experimental method and results for laboratory trials on liquid steel and melting mould powder, with associated discussions, conclusions and outlook.

Realisation of UWB Radar system for meniscus level measurements

The set of requirements of high resolution and high directivity can be met using an ultra-wideband leaky lens antenna. The UWB leaky lens antenna is a linearly polarised antenna constituted by long slots etched on a ground plane that separates a dense dielectric, shaped as a lens [9]. The lens has a dielectric constant of r = 3.27. Figure 2 shows the picture of the antenna.

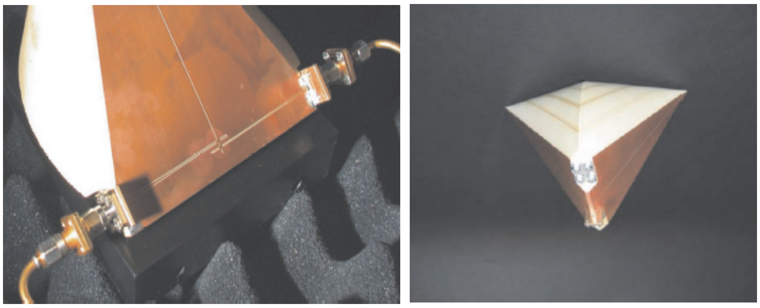

Fig. 2: UWB leaky lens antenna

The UWB antenna has the following features [9]:

• Ultra wide bandwidth: 5 - 40 GHz,

• High directivity: 15 - 20 dBi,

• Low cross-polar radiation,

The phase centre is stable within the frequency range, which means that the measured distance will be the same for every frequency.

Based on this antenna, the RADAR system for laboratory trial of the technology has been constructed, as depicted in Figure 3. The main components of the system are vector network analyzer (NWA), laptop, a fixed leaky lens antenna, a fixed electrical lens, fixed and scanning mirrors, and heat shields. A data acquisition (DAQ) software is installed in the laptop for the purpose of data acquisition and system control. The NWA generates a sweeping signal that excites the UWB radar. The antenna sends out the radar signal and meanwhile receives signals reflected back from target objects.

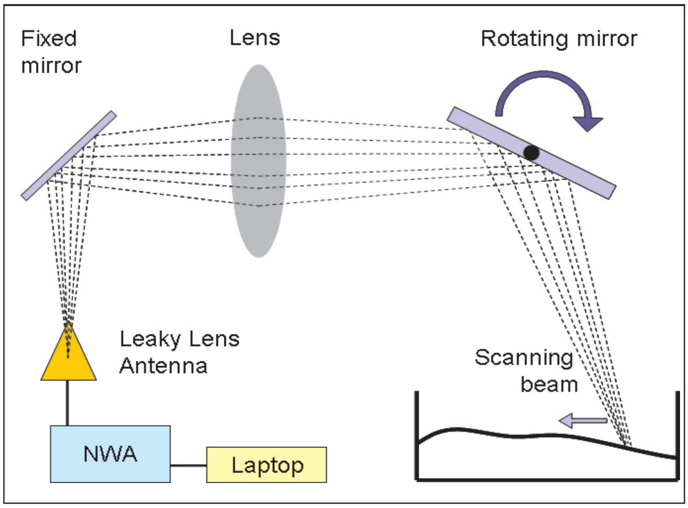

Fig. 3: Schematic drawing of the RADAR system.

The lens is inserted between the antenna and the target object to ensure the focusing of the radar signal to a spot. The spot size reduces with radar frequency due to the frequency dependency of the antenna radiation pattern. The diameters of the focal spot at 5GHz, 15 GHz and 30GHz are 3cm, 1cm and 0.5cm, respectively. The total length of the signal path between the antenna and the target object is 2.5m. Heat shields are used to protect the system from overheating by the high temperature target objects, i.e. liquid steel.

The NWA is a Rohde and Schwarz vector network analyzer ZVA50 having two ports, each with 2.4mm port connector. It can measure both amplitude and phase properties in the frequency range 10MHz - 50GHz [10]. The time domain module ZVAB-K2 is available and allows complex S-parameters to be transformed into the time domain. The sweep rate of the NWA depends on IF bandwidth and the number of points, and is 10 - 20 sweeps per second for typical settings.

System characterisation

System calibration

In order to suppress the influence of radar system itself as much as possible, it would be ideal to have the calibration plane as close as possible to the target object, but evidently, this is technically not feasible. Hence, in a practical system calibration, the calibration plane is at the end of the cable that connects the antenna. A full S11 NWA calibration is done by subsequent connection of a short standard, an open standard and a match (50ohm) standard, using the ZV-Z36 calibration kit from Rohde and Schwarz.

Analysis of system noise

System noise is caused by electronic noise and any instability of system components, such as mechanical vibrations of the radar antenna, mirrors or lens. When the system is calibrated, the mismatch between the calibration data set and the true system data could also contribute to the system noise. In order to study the system response, a number of radar responses of a static target are measured and the average of these responses is (approximately) taken as the true response of the target without the contamination of system noise.

Figure 4 shows the samples of system noise, in the frequency and distance domains, derived from a data set of 1000 measurement sweeps on a steel plate. The source power of the network analyzer is set to be P = 0 dBm, the IF bandwidth is 100 kHz and the sweep size is 4001 over the frequency band 1 - 50GHz. Also shown in the figures are the noise levels in both domains. It is observed from the figures that:

- Noise level is frequency dependent and increases over frequency, which is not surprising for such an ultra-broad bandwidth.
- Noise level is independent for distances higher than 600mm; Below 600 mm, the noise level increases at shorter distances to the antenna.

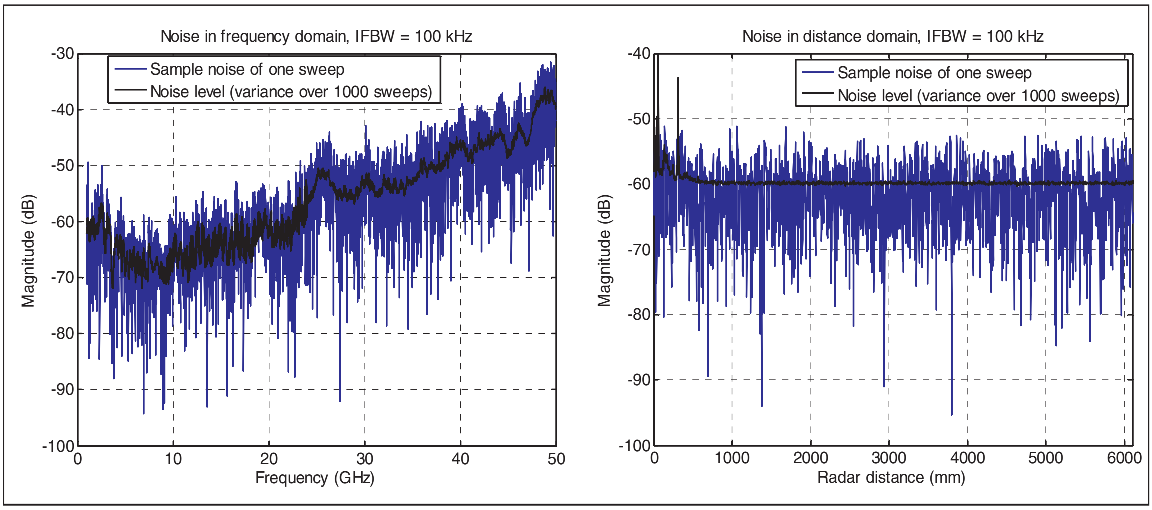

Fig. 4: System noise samples and noise levels in the frequency and distance (time) domains

Clutter and clutter suppression

Since the system is calibrated till the connector between the RF cable and the antenna, the background clutter of a radar response are mainly caused by the connector, the antenna, the lens and the heat shield. We studied the radar responses of these components when there is no target object present. This was carried out by rotating the whole radar system upside down so that the radar signal beam is pointed to the sky. To study the influence of the connector and the antenna, th e antenna was taken out from the system frame and pointed to the sky for a radar measurement.

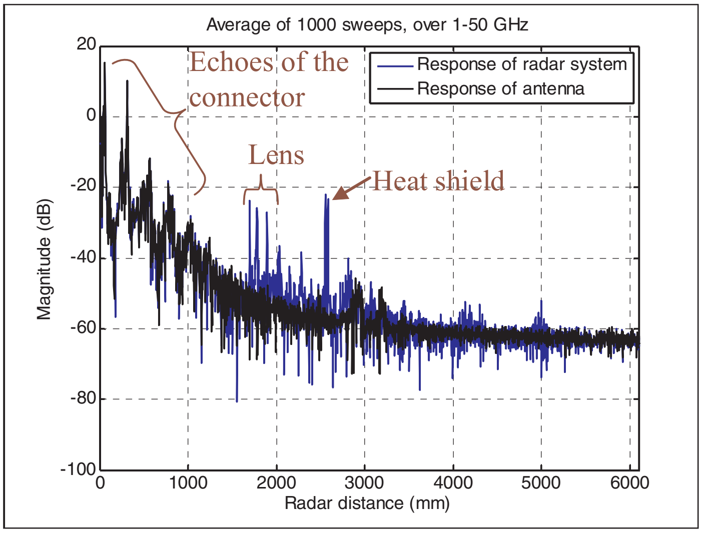

Figure 5: Response in time domain of (a) radar system and (b) antenna only when pointing to sky.

Figure 5 depicts the result of these tests: we observe that the connector between the cable and the antenna is the major source of the background clutter, compared to other components such as the antenna, lens and heat shield. Since the background response contributed by individual system components is rather deterministic, it can be measured in advance and removed from raw radar data. This approach results in a clear signal, in particular "in front of" the target, as demonstrated by Figure 6, where the response is shown obtained using a flat steel plate as target object, before and after (clutter) background subtraction.

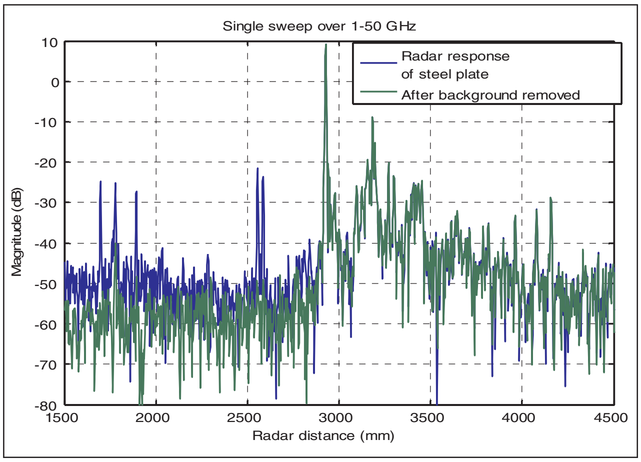

Fig. 6: Radar response of a steel plate with and without the removal of background clutter. System settings: IFBW = 100 kHz, source power P = 0 dBm, sweep size = 4001 over 1-50 GHz.

Here, the peak from the steel plate target is clearly visible. Also notable are the tail responses behind the main peak. These tail responses are contributed by the following factors:

- Echo reflections of heat shield and lens over the
- Echo reflections of the steel plate response over the connector.
- Echo reflections of the steel plate response inside the antenna.

Although the tail causes no problem to the measurement of only one target, it could result in serious interference when measuring two target objects, e.g. measuring the response of meniscus covered by mould powder in a casting mould. The interference by the echo reflections of heat shield and lens may be prevented by increasing the distance between the closest system component, i.e. the heat shield here, and the target object, i.e. the steel plate here. The interference due to the echoes by the connector and reflections inside the antenna, especially the first-order reflections adjacent to the target response, could be suppressed by a more advanced antenna design where matching layers are applied to reduce the internal reflections.

In the present system, we will use de-convolution techniques in the processing of the data to suppress the tail responses. The results of this procedure are demonstrated in the Results section in part II.

Verification of the fixed phase centre

To validate the claim of a fixed phase centre of the leaky lens antenna, the spectrum has been divided (in the post-processing) into spectra with band width of 10 GHz. See Figure 7, where the distance spectrum has been zoomed in on the zone around the target position. The fact that the peak position for the 4 different spectra is located on exactly the same distance evidences that the phase centre of the antenna is indeed fixed and not shifting as a function of the frequency.

Conclusions

In this paper, we have highlighted the design and construction of the ultra-wideband radar system for laboratory trials to investigate the potential of recent RADAR developments for monitoring of the meniscus level and the slag layer thickness during continuous casting. In particular the incorporation of a leaky lens antenna, which is capable to produce an ultra-wideband, directed beam with a fixed phase centre over the entire frequency range, makes this technology well suited for highly resolved measurements of the level of (liquid) metal and thickness of dielectric media. Extensive pre-processing of the data, including suppression of system noise and clutter, as well as de-convolution is necessary to achieve improved signal-to-background ratio up to about 50 dB.

Acknowledgements

TNO-DSS, in particular Caspar Lageweg, Eric van der Houwen, Frans Nennie, Noud Maas, Ton Overtoom, Michiel Bruijn, Christiaan Lievers and Bram Wittens are acknowledged for their contributions for the design and realisation of the RADAR system.

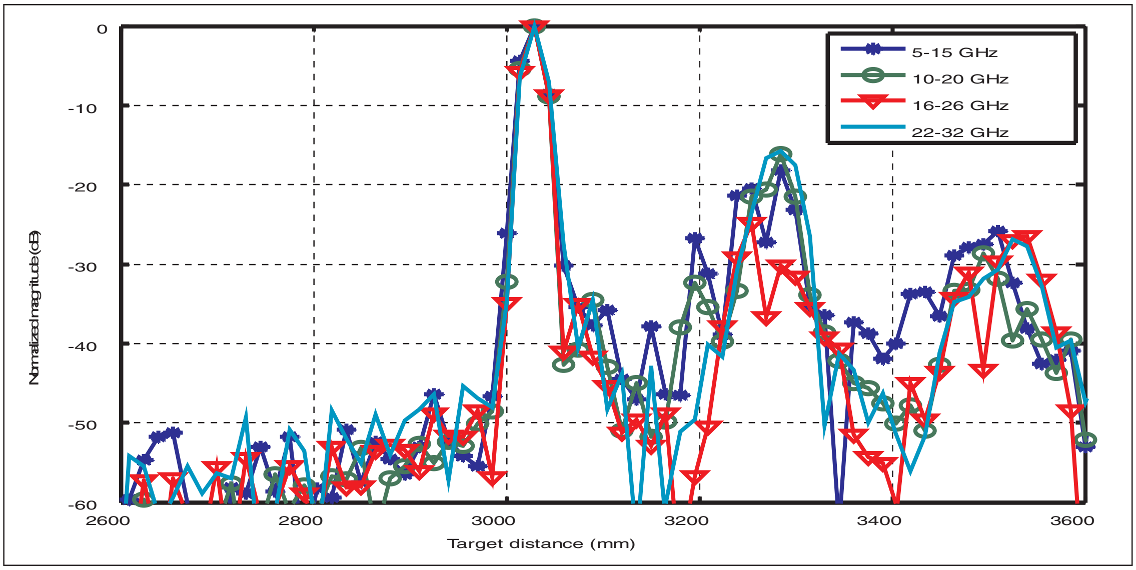

Fig. 7: Radar responses with 10-GHz bandwidth

References

1. Kim, G., Kim, H., Oh, K, Park, J., Jeong, H., Lee, E., "Level meter for the electro-magnetic continuous casting of steel billet", ISIJ International, 43(2003), No.2, p. 224
2. Clymans, D.,"An enhanced eddy current level control system in continuous casting", La Revue de Metallurgie-CIT, Juin 2000
3. http://www.vuhz.cz, retrieved on 02 Oct 2011.
4. http://www.berthold.com, retrieved on 02 Oct 2011.
5. M. Skolnik: Radar Handbook, 2nd edition, McGraw Hill 1990, ISBN 0-07-057913-X
6. D. Malmberg and L.B. Bååth, Slag level detection in EAFs using microwave technology, Scandinavian Journal of Metallurgy ISSN 0371-0459, 2000
7. D. Malmberg, P. Hahlin, E. Nilsson: Microwave Technology in Steel and Metal Industry, an Overview, ISIJ Int., 47 (4) (2007)533-538.
8. D. Malmberg, J. Björkvall, J. Malm and L.B. Bååth: Preliminary microwave measurements on liquid slags, Iron and Steelmaking, 32(1) (2005) 61-67.
9. A. Neto, S. Bruni, G. Gerini, M. Sabbadini "The Leaky Lens: a Broad Band, Fixed Beam Leaky Wave Antenna" in IEEE Trans. on antennas and Propagation, 53 (10), October 2005
10. Operating Manual and Datasheets of ROHDE & SCHWARZ Vector Network Analyzer ZVA 50 on website: http://www.rohde-schwarz.com/, retrieved on 02 Oct 2011.