94GHz makes sense of bulk material measurements

For many years the higher millimetre-wave frequencies, notably 94GHz, were the preserve of military systems. More recently, however, the increasing availability of cost-effective components at these frequencies has made them a viable option for industrial non-contact sensors. Millimetric sensors have the advantage that, unlike ultrasonic or laser sensors, they work well in dusty or foggy environments.

Figure 1: The ELVA-1 94GHz FMCW sensor for non-contact level measurement applications

Mines

An example of this is the Russian-made ELVA-1 FMCW 94/10 millimetre wave distance sensor, which is a high-accuracy non-contact level measurement system that has been designed for use in measuring large volumes of bulk materials in hoppers and silos at mineral extraction sites and chemical plants, to control raw material inventory. Examples of its use are found in hard-rock mines, cement hoppers, and other large receptacles that suffer from adverse environmental conditions such as dust, corrosive gas, fog, or high-level noise. The distance sensor can also be used for liquid level measurement in large industrial tanks where the edge of the liquid is indeterminate because of foam or vapour - volume measurement in large brewery tanks is a particular example.

The most popular types of sensor for non-contact level measurement are laser, acoustic, microwave radar and millimetre wave radar. Although laser and acoustic sensors work well in liquid level measurement, they become useless under conditions of high dust level, strong air current and extremely high noise (underground blasting) that are common in hard-rock mines or quarries. In the case of the microwave radar sensor, its wide beamwidth limits its use in deep ore passes or small-diameter bunkers and prevents its use for exploring surface profile, which is an important parameter for determining the actual volume of substance in the bunker.

Distance sensor resolution	0.1m
Range of heights of sensor position above the surface of material	0.6m to 300m
Deflection of the sensor axis from the vertical line	≤1°
Distance sensor radar transmitter emission power	10mW
Distance sensor radar operating frequency	94GHz
Distance sensor radar power consumption	20W
Ambient temperature	-30 to +50°C
Atmospheric pressure	84.0 - 106.7 kPa (630 - 800 Torr)
Relative humidity at 35°C and lower	≤95%
Vibration amplitude at 5Hz to 25Hz band	≤0.1mm

Table 1: FMCW 94/10 distance sensor specifications

Sensor

The ELVA 94GHz distance sensor, shown in Figure 1, is based on the FMCW (frequency-modulated continuous wave) radar principle, which provides a good choice where signal linearity, high sensitivity, cost and reliability are priorities. The 3mm free-space wavelength allows for good penetration of dust and water vapour, and allows a narrow beam to be produced without the need for an excessively large antenna. It has been shown to work even with a film of dust covering the antenna. The operating range of the distance sensor is 300m, allowing its use in deep mines, where typical passes are 50 - 150m or occasionally longer.

For ease of use the sensor is built as two modules; a front end and a separate signal processing unit, the two being connected by a 10m shielded cable. A local graphics display and keypad are incorporated into the control unit. The front end and antenna is housed in robust metal case, giving the unit a total weight of 8kg.

Output power is typically 10mW. The signal processing unit, which is built into a commercially available housing, weighs 1.5kg. Table 1 summarises the main performance parameters of the sensor unit, which operates from a 110/220V AC supply.

Field test

The performance of the sensor was tested in the field in a real-life situation in the nickel mines belonging to Inco's Mines Technology Department in Copper Cliff, Ontario, Canada. A comparative experiment was run in collaboration with ELVA-1's Millimetre Wave Division and Soquelec Telecommunication, ELVA's representatives in Canada. The low power 10mW, 94 GHz sensor was used.

During the experiment, a laser sensor was tested side-by-side with the millimetre-wave sensor. To simulate an opaque dust cloud, a bag of cement and ore dust was dispersed in a mine tunnel using compressed air and powerful fans as shown in Figure 2.

Figure 2: Testing the operation of the millimetre-wave sensor through a cloud of cement dust in a nickel mine

A large underground vehicle, 50m distant from the sensors was used as a target. The experiment showed that the prototype FMCW distance sensor easily penetrated the cement dust, and that the target echo was clearly visible on the data collection PC. At the same time the laser sensor lost sight of the target as soon as the dust cloud reached the sensor beam.

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Evaluating errors in sensor processing

When millimetric sensors are to be used in safety applications such as automotive braking systems, the acquisition of very precise information is required. In a paper at last year's European Microwave Conference in Milan, Venot and Wiesbeck of Institut für Höchstfrequenztechnik und Elektronik at Karlsruhe University in Germany evaluated a 76.5GHz near field sensor that was intended to detect distance variations with a resolution of a few micrometres within a range of some centimetres.

Various applications of such a sensor are possible, including eccentricity detection of rotating objects, derivation of speed of revolution and surface roughness control. This would have applications to various complex mechanical systems and machines that currently do not have any sensors to control the performance of rotating and moving machine parts - bearing slackness, system vibrations or the torsion of a driving shaft - or that currently use acceleration sensors to detect vibrations, inductive sensors for rotation velocity measurement or optical equipment for torsion measurement.

Rotation

The objective of the mm-wave radar sensor is to offer a contact-free measurement system for various applications such as these. The main challenge is to realise such a sensor in a compact outline operating in the very near field, for example directly in front of a rotating turbine shaft, in contrast to existing millimetric sensors such as vehicle proximity radars that are optimised for far-field sensing.

The concept of the multipurpose near-field radar sensor had been described in a paper by the same team at the 31st European Microwave Conference in 2001. In this follow-up paper both the acquisition and calibration of the millimtre-wave analogue raw data and the further signal processing of the base band data in time and frequency domain was presented.

Because the sensor operates in the very near field, the non-linear properties of the transmitted and received signals have to be considered. By developing a special antenna adapted to the sensor it was possible to reduce the impact of the near field phenomenon, especially the evanescent modes very critical in this range, but to achieve the required accuracy a high precision phase measurement is necessary.

Field

Calculating the field using HFSS and Feko, and performing measurements for comparison and verification, a transformation of the received backscattered data was developed allowing linear distance measurement. This was based on the exact knowledge of all sources producing errors in the receive signal path, which can be divided into errors occurring in the sensor module and errors due to the transmission path between sensor and object. A complex parameter model of the sensor circuit was established to assess the impact of the various errors

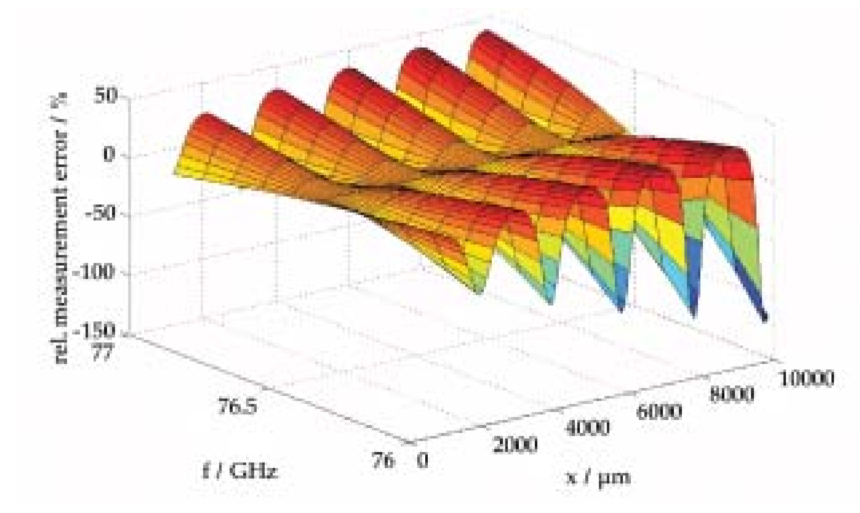

Figure 1: Calculated normalised measurement error depending on the absolute distance and frequency drift

and to define an error compensation vector. The most important error sources are the matching of the antenna and the direct coupling of the transmission signal into the receive path, both introducing an error in the same power range as the received signal. Other errors are variations of the circuit dimensions due to manufacturing tolerances and phase errors of the I/Q demodulator at the centre frequency 76.5GHz.

Calibration

The sensor system errors are not dependent on the absolute distance, and can be compensated by a single constant complex calibration error vector, derived using an iterative calibration algorithm that compensates sensor phase errors, direct coupling, antenna matching and frequency shift for the whole measurement range, and multiscattering up to a limit value dependent on the absolute distance. The algorithm is based on a variance analysis of the normalised phase and amplitude derivation at two frequencies in a bandwidth of 3GHz. Figure 1 shows the measurement error derived from the normalised phase derivation at a range of 10mm for a centre frequency of 76.5GHz and a frequency shift due to temperature up to 1GHz.

The methodology of the baseband and signal processing was described in some detail, and finally measurement results of a turbine shaft in a power generating station rotating at 10Hz were presented, indicating that an accuracy of better than 5µm was achievable, with as good as 2µm possible under laboratory conditions, despite an eccentricity of 30µm.

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