SENSING OF IRREGULARITIES ON FAST MOVING SURFACES BY MICROWAVES AND MILLIMETERWAVES

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ABSTRACT

Fine cracks and irregularities on a fast moving conducting surface were detected by the use of microwave and millimeter wave radio responder techniques. The interrogation angle was restricted to an oblique incidence angle less than ±0.5 degree from the surface. The fast moving conducting surface was surrounded by both fast moving and stationary reflective conducting structures. Experimental methods and results from a fine crack 0.1 mm wide, 0.9 mm deep, and 25 mm long on a conducting surface travelling with a speed of 20.23 m/s and measured at 10.525 GH_z and 73 GH_z are presented.

The reflection-type microwave radio responder consisted of a 10.525 GH_z 50 mW Gunn diode cw transmitter, a circulator, and a horn antenna used as the interrogator. The receivr in the same responder consisted of the same horn antenna, the circulator and detector diode. The detector diode output was observed with a Norland 3106R digital memory oscilloscope. A reflex kylstron VA 250 was used as the transmitter signal source for the millimeter wave responder. There was a distinct difference between the responder output patterns with uncracked and cracked surfaces. It is therefore possible to use this type of responder for hair-line crack detection of fast moving conducting surfaces. It was also found that this type of radio responder can detect the surface irregularity even before the hairline crack actually occurs. Key words: microwave radio responders, millimeter wave radio responders sensors.

INTRODUCTION

The objective of this paper is to report a new finding of microwave and millimeter wave radio responder capability to sense irregularities of fast moving surfaces. The surface irregularities involved in this case are hairline cracks on metallic surfaces. Microwave radio responders (1)(2) are considered to be a form of a degenerated bistatic radar (3)(4). The interrogating transmitter and the echo-catching receiver are located at the same location. The surface to be monitored is interrogated by radiation of microwaves or millimeter waves from a remotely located transmitter. A portion of the back-scattered waves from the surface is caught by a remotely located receiver. The back-scattered waves contain information about the surface.

In previous studies of radio responders (1)(2), targets interrogated were stationary and the interrogating waves were sent at a normal angle to the surface to be monitored. Appreciable echoes were expected in the past. In this paper the interrogating radiation beam is sent in an oblique angle to the surface. Therefore very little back-scatter from the monitored surface can be expected. In addition, the fast moving test surface is also placed among other moving and stationary metallic objects. Therefore, the echo to this radio responder contains strong echoes from surrounding structures and very little back-scatter from the moving surface to be monitored. Under these rather severe conditions, irregularity monitoring capability of the microwave and millimeter wave responders were evaluated.

A new data processing technique involving a digital memory oscilloscope was applied to produce the reported sensitivity. In this new technique the radio responder memorizes a pattern of back-scattered radiation. When the radio responder receives an irregular pattern of back-scattered waves, the difference will be displayed at the output. By observing the irregularity of the output display pattern, the observer can detect the presence of hair-line cracks or even signs predicting the actual appearance of hair-line cracks on the surface.

EXPERIMENTAL SET-UP AND PROCEDURE

Microwave Radio Responder

A schematic diagram of the microwave radio responder experiment is shown in Fig. 1. The target has a motor coupling disc of 15.16 cm diameter driven by an electric motor with the speed of 2846 r.p.m. This allowed a tangentical speed of 20.23 m/s. The surface of the rotating coupling disc was monitored. The two shafts coupled by this motor coupler were slightly misaligned so that the coupling will develop cracks within a reasonable time period.

Microwave signals were generated by the use of a 10.525 GH_z, 50 mW, Gunn diode oscillator. Generated microwaves were fed to a X-band 15 dB pyramidal horn antenna through a X-band circulator. The microwave horn antenna was placed 5 cm from the rotating surface of the coupling disc with an oblique angle of 0.5 degree from the surface to be monitored. Microwaves were launched toward the rotating surface of the motor coupling disc with the oblique angle of incidence 0.5 degree. Therefore most of the microwave energy hitting the coupling surface bounced forward with little energy scattering backward from the coupling surface. Within this small amount of back-scattered energy, the information of the monitored surface condition was included. The small amount of back-scattered waves was caught by the same horn antenna and the received back-scattered waves were fed to a microwave detector through a microwave circulator. The received microwave was detected and kept in the memory of a digital memory oscilloscope. The oscilloscope memorized the received signal pattern under normal surface conditions. When an irregularity appears or is about to appear on the monitored surface, the pattern of detected waveform changes. The display of the difference in the responses under normal and abnormal conditions signifies the presence of an abnormality on the monitored surface.

In this microwave experiment the direction of the electric field vector of interrogating microwaves was set perpendicular to the surface of the coupling disc to be monitored for better sensitivity. The waveguide components employed in this experiment are all standard X-band waveguide components.

Millimeter Wave Radio Responder

In the millimeter wave experiments, a test configuration similar to the one shown in Fig. 1 was used. All waveguide components were standard M-band waveguide components. The motor coupling and the digital memory oscilloscope were the same as the microwave experiment. Millimeter waves were generated by a reflex klystrom VA 250 at a transmitter frequency of 73 GH_z. In this case, to obtain the best sensitivity for hairline crack detection, the electric field vector of interrogating millimeter waves was oriented parallel to the surface of the coupling disc for better sensitivity.

PRINCIPLES OF EXPERIMENTS

Qualitative Explanation

As seen from Fig. 1, microwave or millimeter waves were generated at the signal generator. The output was fed to the output waveguide which was connected to a circulator. The circulator sent the microwave signal to a horn antenna but not directly to the microwave detector Microwaves fed to the horn antenna were launched from the horn antenna and irradiated the surface of the rotating motor coupling in an oblique angle as shown in Fig. 1. Microwave radiation hitting the surface of the coupling produced back-scattering. The amount and response pattern in time domain of the back-scattering depended on the reflective and scattering condition of the surface. The presence of hairline cracks or bulging prior to appearance of hairline cracks produced a change in the time-domain pattern on the back-scattering microwaves. Back-scattered microwaves from the surface of the motor coupling was received by the same horn antenna as seen in Fig. 1. The received scattered microwaves by the horn antenna was then sent to the circulator as seen in Fig. 1. The circulator sent the received back-scattered waves to the detector, not toward the signal generator. Thus the circulator separated the received microwaves from the transmitting microwaves. The detected received microwaves were processed using a digital memory oscilloscope as shown in Fig. 1. The oscilloscope memorized the time-domain pattern of back-scattered microwaves of a normal surface. When there was a change in the time-domain pattern due to changes in the surface condition, the scope memorized the new pattern and the different pattern can be displayed. By inspecting the correlated pattern, one can recognize the condition of the surface, namely that a hairline crack is about to occur, or a hairline crack actually took place.

Analytical Considerations

As seen from Fig. 1, in this microwave radio responder system, the information on the interrogated surface is contained in the back-scattered microwaves. By processing the signals carried by the received microwaves at the horn antenna, the condition of the interrogated surface can be determined.

When the surface in question located at co-ordinate radius vector $\bar{r}'$ is irradiated by interrogating microwaves of electric field strength vector $\bar{E}^i(\bar{r}')$ and magnetic field strength vector $\bar{H}^i(\bar{r}')$, by Ampere's Law and Faraday's Law, the conduction current density $\bar{J}_i(\bar{r}')$ and the magnetic current density $\bar{M}_i(\bar{r}')$ will be induced at a point $\bar{r}'$ on the surface in question. The location of the point in question is represented by a spherical coordinate radius vector $\bar{r}'$.

By Ampere's Law
$$\bar{n} \times \{\bar{H}^i(\bar{r}') - \bar{H}^s(\bar{r}')\} = \bar{J}_i(\bar{r}') \tag{1}$$

where $\bar{n}$ is the outward normal unit vector to the surface.

By Faraday's Law
$$\bar{n} \times \{\bar{E}^i(\bar{r}') + \bar{E}^s(\bar{r}')\} = \bar{M}_i(\bar{r}') \tag{2}$$

Now both $\bar{J}_i(\bar{r}')$ and $\bar{M}_i(\bar{r}')$ can be redefined as

$$\bar{J}_i(\bar{r}') \equiv \bar{J}_o(\bar{r}') + \bar{J}_s(\bar{r}') \tag{3}$$

where
$$\bar{J}_o(\bar{r}') \equiv \bar{n} \times \bar{H}^i(\bar{r}') \tag{4}$$

This is induced by $\bar{H}^i(\bar{r}')$

$$\bar{J}_s(\bar{r}') \equiv - \bar{n} \times \bar{H}^s(\bar{r}') = - \bar{n} \times \dot{\rho}(\bar{r}')\bar{H}^i(\bar{r}') \tag{5}$$

where $\dot{\rho}$ is the scattering coefficient. This current induces scattered magnetic field $\overline{H}^s(\overline{r}')$, but it is supported by $\overline{H}^i(\overline{r}')$.

Now $$\overline{M}_i(\overline{r}') \equiv \overline{M}_o(\overline{r}') + \overline{M}_s(\overline{r}') \tag{6}$$

where $$\overline{M}_o(\overline{r}') \equiv - \overline{n} \times \overline{E}^i(\overline{r}') \tag{7}$$

This is induced by $\overline{E}^i(\overline{r}')$

$$\overline{E}^s(\overline{r}) = \iiint_{v'} \overline{\overline{G}}_1(\overline{r}/\overline{r}')\cdot\left[j\omega\mu\overline{J}_s(\overline{r}') + \nabla' \times \overline{M}_s(\overline{r}')\right] dv' \tag{8}$$

This current induces $\overline{E}^s(\overline{r}')$, but it is supported by $\overline{E}^i(\overline{r}')$.

Therefore, both $\overline{J}_s(\overline{r}')$ and $\overline{M}_s(\overline{r}')$, in turn, re-radiate scattered wave sin different directions in various radiation intensities. The back-scattered radiation bounces back to the horn antenna of the radio responder. The electric field $\overline{E}^s(\overline{r}')$ and magnetic field $H^s(\overline{r}')$ of back-scattered microwaves reach the responder horn antenna located at the co-ordinate radius vector $\overline{r}$ are expressed by (5)

$$\overline{E}^s(\overline{r}) = \iiint_{v'} \overline{\overline{G}}_1(\overline{r}/\overline{r}')\cdot\left[j\omega\mu\overline{J}_s(\overline{r}') + \nabla' \times \overline{M}_s(\overline{r}')\right] dv' \tag{9}$$

$$\overline{H}^s(\overline{r}) = \iiint_{v'} \overline{\overline{G}}_2(\overline{r}/\overline{r}')\cdot\left[j\omega\mu\overline{M}_s(\overline{r}') - \nabla' \times \overline{J}_s(\overline{r}')\right] dv' \tag{10}$$

where $\overline{\overline{G}}_1$ is $(\overline{r}/\overline{r}')$ the Green's diadic of the first kind and ($\overline{\overline{G}}_2(\overline{r}/\overline{r}')$ is the Green's diatic of the second kind (4). v' is the volume where $\overline{J}_s(\overline{r}')$ and $\overline{M}_s(\overline{r}')$ distributes. ω is the operating angular frequency of microwaves. Therefore if $\overline{J}_s(\overline{r}')$ and $\overline{M}_s(\overline{r}')$ corresponding to normal surface are $\overline{J}_{SN}(\overline{r}')$ and $\overline{M}_{SN}(\overline{r}')$ respectively then these surface currents produce normal electric and magnetic fields at the responder horn antenna as

$$\overline{E}^s_N(\overline{r}) = \iiint_v \overline{\overline{G}}_1(\overline{r}/\overline{r}') \cdot \left[j\omega\mu\overline{J}_{SN}(\overline{r}') + \nabla' \times \overline{M}_{SN}(\overline{r}')\right] dv' \tag{11}$$

$$\overline{H}^s_N(\overline{r}) = \iiint_v \overline{\overline{G}}_2(\overline{r}/\overline{r}') \cdot \left[j\omega\overline{M}_{SN}(\overline{r}') - \nabla \times \overline{J}_{SN}(r')\right] dv' \tag{12}$$

If there is an abnormality on the surface to be monitored the currents are no longer $\overline{\overline{J}}_{SN}(\overline{r}')$ and $\overline{M}_{SN}(\overline{r}')$. The currents on the surface turn into different sets of distribution represented by $\overline{J}_{SA}(\overline{r}')$ and $\overline{M}_{SA}(\overline{r}')$. This results in different sets of electric field $\overline{E}^s_A(\overline{r})$ and magnetic field $\overline{H}^s_A(\overline{r})$ at the responder horn antenna.

$$\bar{E}^s_A(\bar{r}) = \iiint_{v'} \bar{\bar{G}}_1(\bar{r}/\bar{r}') \cdot [j\omega\mu\bar{J}_{SA}(\bar{r}') + \nabla' \times \bar{M}_{SA}(\bar{r}')]\, dv' \tag{13}$$

$$\bar{H}^s_A(r) = \iiint_{v'} \bar{\bar{G}}_2(\bar{r}/\bar{r}') \cdot [j\omega\mu\bar{M}_{SA}(\bar{r}') - \nabla' \times \bar{J}_{SA}(\bar{r}')]\, dv' \tag{14}$$

Therefore the field strength differences from the normal surface condition are

$$\Delta\bar{E}^s(\bar{r}) \equiv \bar{E}^s_A(\bar{r}) - \bar{E}^s_N(\bar{r})$$

$$= \iiint_{v'} \bar{\bar{G}}_1(\bar{r}/\bar{r}') \cdot [j\omega\mu\{\bar{J}_{SA}(\bar{r}') - \bar{J}_{SN}(\bar{r}')\} + \nabla' \times \{\bar{M}_{SA}(\bar{r}') - \bar{M}_{SN}(\bar{r}')\}]\, dv'$$

$$\neq 0 \tag{15}$$

$$\Delta\bar{H}^s(\bar{r}) \equiv \bar{H}^s_A(\bar{r}) - \bar{H}^s_N(\bar{r})$$

$$= \iiint_{v'} \bar{\bar{G}}_2(\bar{r}/\bar{r}') \cdot [j\omega\mu\{\bar{M}_{SA}(\bar{r}') - M_{SN}(\bar{r}')\} - \nabla' \times \{\bar{J}_{SA}(\bar{r}') - \bar{J}_{SN}(\bar{r}')\}]\, dv'$$

$$\neq 0 \tag{16}$$

Under normal conditions $\Delta\bar{E}^s(\bar{r}) = 0$ and $\Delta\bar{H}^s(\bar{r}) = 0$. Therefore monitoring $\Delta\bar{E}^s(\bar{r})$, it is possible to sense the abnormality of the surface. After repeated observation it is possible to correlate the time domain pattern of $\Delta\bar{E}^s(\bar{r})$ and the kind of the abnormality. The principles stated about microwave radio responders are also applicable to millimeter wave radio responders.

EXPERIMENTAL RESULTS AND REMARKS

Microwave Radio Responder

Experimental results of the microwave radio responder operated at 10.525 GHz is shown in Fig. 2. The time domain patterns of $\Delta\bar{E}^s(\bar{r})$ observed at the memory oscilloscope are shown. $\Delta\bar{E}^s(\bar{r})$ for a normal surface and the pattern after a hairline crack of 0.1 mm wide 0.9 mm deep and 25 mm long was produced on the moving surface of a motor shaft coupler rotating with the tangential speed of 20.23 m/s are shown.

Millimeter Wave Radio Responder

As shown in Fig. 3, when the responder was operated at 73 GHz, similar results as shown in Fig. 2 were obtained. It can be concluded that, because the VA250 klystron has 10 dB less power than an X-band gun oscillator, the millimeter wave radio responder is more sensitive than the microwave radio responder.

If the structure to be interrogated permits the interrogation direction to be other than the oblique incidence angle and/or the transmission type responder (1) rather than reflection type responder can be utilized, then detection sensitivity can be increased. Under certain industrial conditions, this microwave radio responder approach of irregularity detection on a fast moving conducting surface is not only complimentary to the optical or ultrasonic approaches, but it exceeds also these alternatives.

CONCLUSIONS

The experimental results show that the microwave or millimeter wave responder techniques are effectively applicable to detect surface irregularities such as a narrow and shallow hairline crack on fast moving conducting surface. The surface to be interrogated can be surrounded by spurious metal structures so long as the interrogation waves can reach the surface to be interrogated. The interrogation angle is solely restricted to the oblique incidence angle in this test.

ACKNOWLEDGMENT

The author thanks Dolores Marrari, John Natzke, Mark R. Wolski, and M. Michael Ishii for their assistance in preparation of this manuscript.

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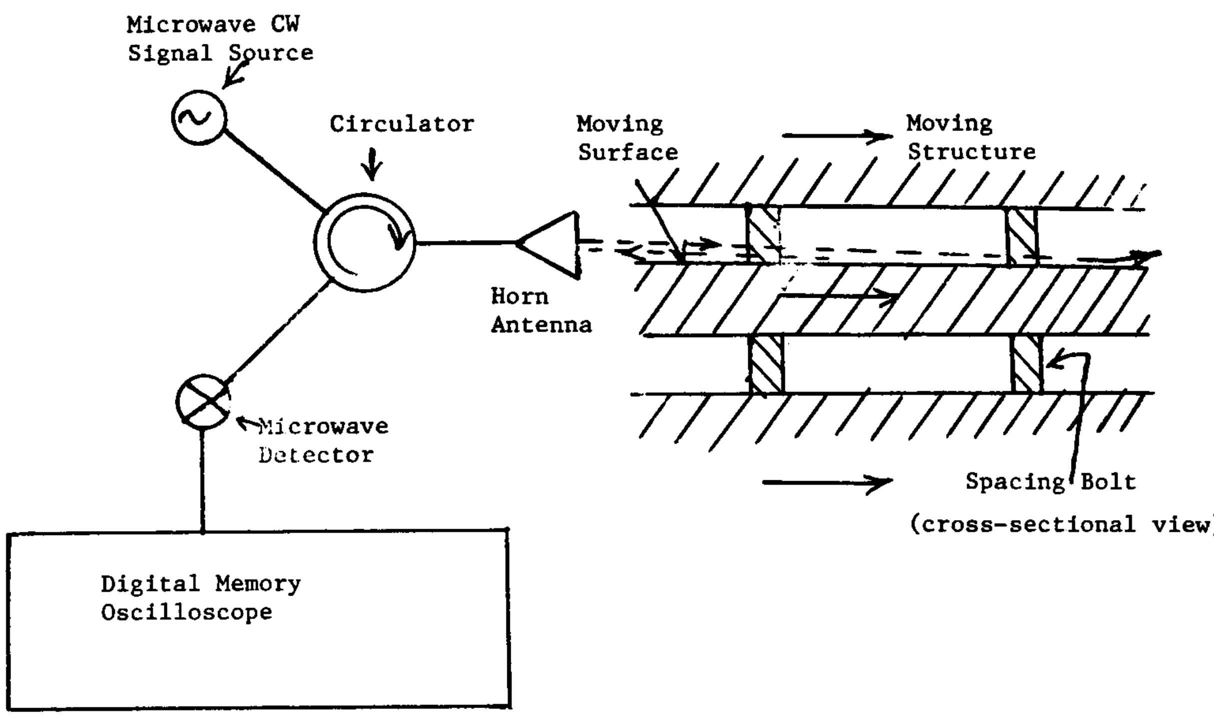

Fig. 1. A schematic diagram of experimental set-up to monitor moving surface irregularity by a microwave technique. The electric field vector is perpendicular to the moving surface for 10.525 GHz experiments and it is parallel for 73 GHz experiments.

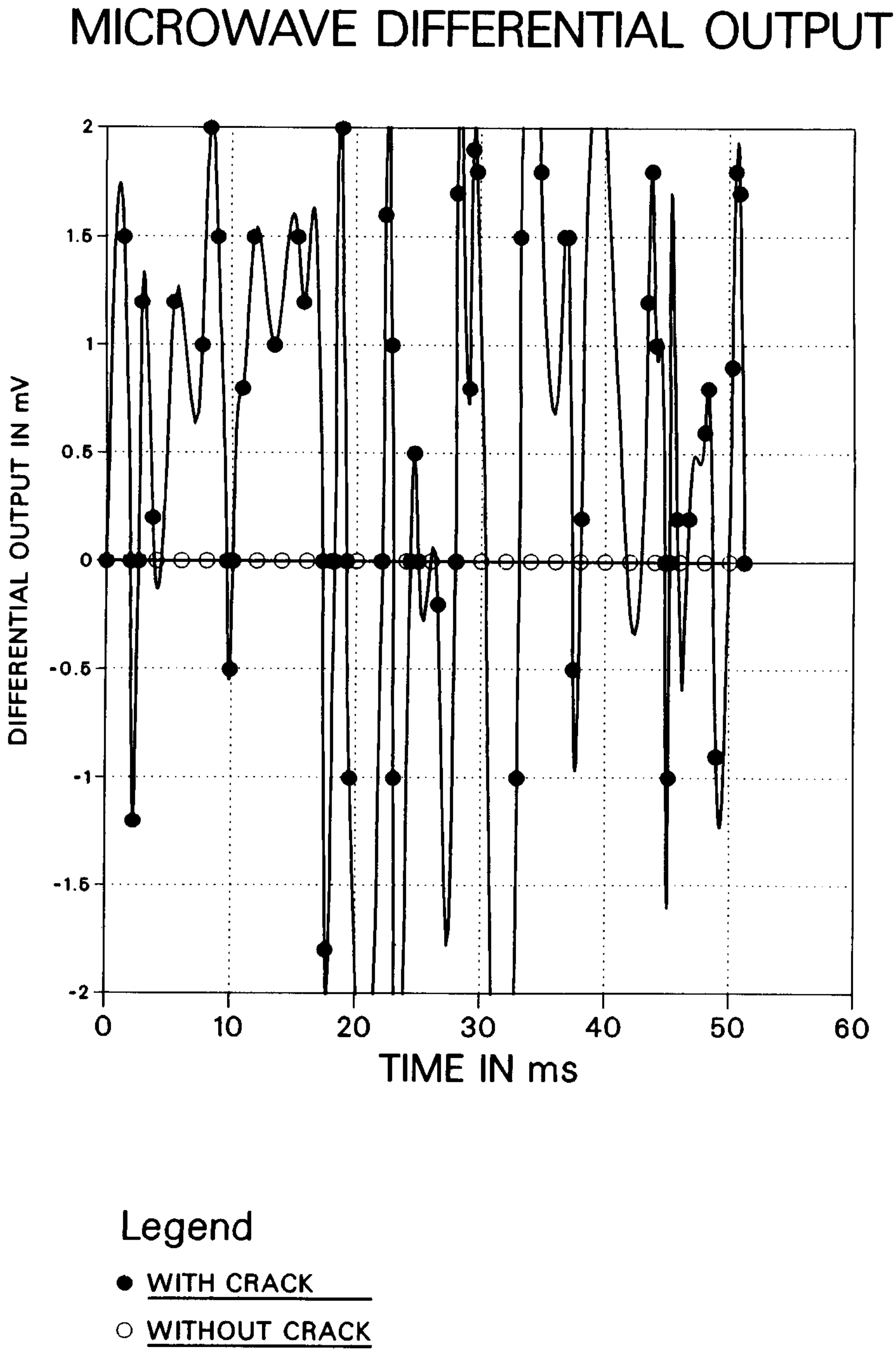

Fig. 2 Differential output of microwave radio responder.

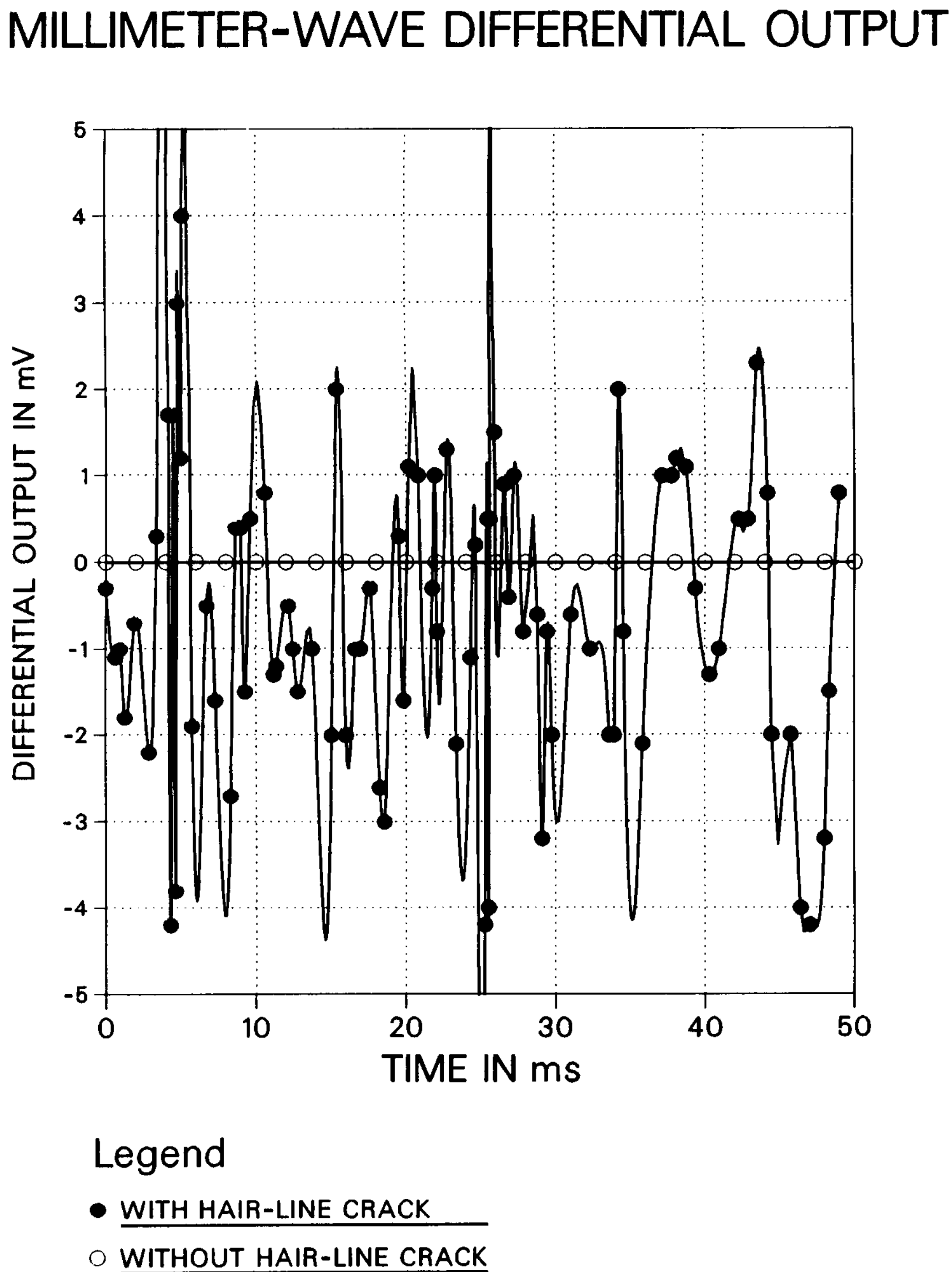

Fig. 3 Differential output of millimeter-wave radio responder.