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Dopler Radar in Crack Testing

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Authors' contributions

This work was carried out in collaboration between both authors. Author VS designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript and managed literature searches. Author SB managed the analyses of the study and literature searches. Both authors read and approved the final manuscript.

Short Research Article

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ABSTRACT

A unique phenomenon in physics has been revealed. Due to internal mechanical stress and defects the surface electrical conductivity of metallic objects can be modified. This conductivity modification even exists for some time after the failure of the mechanical attack. The data presented in this paper proves the effectiveness of the discovered phenomenon. Designed microwave sensor reveals remote closed metal defects. Experiments in detecting cracks within rail-wheel rims were one of the first applications.

Keywords: Doppler radar; active defects in metals.

1. INTRODUCTION

Modern non-destructive metal testing methods are based on well-known physical phenomena. Ultrasonic, acoustic-emission and radio-wave units detect metal structural discontinuity of up to some fractional millimeters [1,2,3]. Comparing not only the sample measurement results with discontinuity, but also measurement results of samples with and I or without defects provide a means to evaluate the accuracy of each method, cost of measurement, and further, the effectiveness of determining metal structure defect and / or material fatigue. During the last few decades engineers have been mainly involved in implementing acoustic-emissive testing equipment. In contrast to previous methods, the acoustic emission method does not detect abstract discontinuity, but detects more precisely

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those areas of exhausted elastic interaction sources, which are on the verge of failure under mechanical loading in construction and objects.

Those defects which generate acoustic waves are the initial points of dangerous mechanical stress. Although this method is favorably different from other ones, it has several "undesirable" properties. The "idle" mode should be observed in the acoustic-emission method. Any external mechanical noise sources result in the decrease of the method effectiveness. In this case, it is necessary to apply contact piezoelectric sensors for mechanical surface waves, which, in its turn, excludes the possibility of examining moving objects, as well as those surfaces heated up to more than 500ºC. Another specific feature includes the fact that the defects could be detected only under mechanical (thermal) loading. The generation of acoustic signals trail off immediately after the termination of the loading itself. The task stated in the following paper is to determine the ultrasonic waves on the metal surface by microwave sensor [4].

Desired surface waves should have emerged in response to acoustic emission sources. However, numerous experiments did not furnish the targeted results for a long time. Even when the stationary ultrasonic waves of 5-6 nanometers emerged in response to a simulator (piezoelectrical sensor) and at the excited amplitude of 80-90 V (47-50 KHz), it was impossible to register the modulation of sensor high-frequency oscillations (10-37GHz). The simple calculation proved the fact that the above-mentioned effect is impossible at the level of those signals registered by existing class-devices under ambient temperature of 300ºK [5] . To the contrary, the testing experiments continued as many domestic engineers, as well as, those abroad were interested in such an interaction-free defect detection option [6,7,8].

An experimental break-through that may succeed only by chance. Eventually, in 1995, on testing the next cracked sample excited by ultrasonic-simulator activity, emerging spectral components of ultrasonic frequency from microwave sensor output were registered [9].

The following observed effect could have been explained as a result of the theoretical research completed by Russian engineers [10]. The outcome was the designed equipment, i.e. instrument kit "Remote Indicators of Active Defects" (RIAD), which, in its turn, furthered the implementation of test runs in remote detection of closed defects in different materials, including steel, aluminium, copper and lead.

Alternatively, the breakthrough was that the amplitude of equivalent ultrasonics in metal with cracks was 190 times greater than in stated calculations. An additional point is that the length of surface conductivity waves, registered by microwave sensor, was notably different from the length of ultrasonic waves 1000-fold. Observed phenomenon was quite unique in the fact that it had not been described earlier, but also it was contradicting to those specified results obtained by Acoustic Emission method. Metal experiments proved that the discussed breakthrough could be applied for direct diagnostics of constructions and objects without maintaining "idle" mode. In this case, the desired signal emerges on the metal surface in the presence of defects. Special defects "active" ones, when applying the Acoustic Emission method, retain their distinctive features after the mechanical stress relief. This peculiar phenomenon involves additional ultrasonic signal attack on the zone of the active defect (zone of recently ex-active defect) generating distinctive modulation. Surface electrical conductivity modulation occurs throughout the entire construction all the object. Power spectral density of an ultrasonic signal (15-20 W/Hz) is more or less higher than that of the spectrum density of random mechanical signals (2-5 W/Hz), which frustrate the "idle" mode itself. Consequently, the desired signal of "surface conductivity modulation", could not be registered even under conditions of interfering industrial signals. Analyzer of spectral microwave sensor output signals detects desired signal of ultrasonic frequency at the level of interfering signals. In contrast to the Acoustic Emission method applied in equipment under conditions of unwanted noise it is possible to precisely detect either the presence or absence of defects of different activity rates, accompanying failure origin in real-time and motion without shutdown. Defects can be detected not only in the remote but also in the interaction-free regime. Operating distance is limited due to the possibilities of focusing the microwave field on investigated surface (ranging from 100mm to several kilometers). The emerging speed of desired signal equals light speed in the metal and exceeds sound speed up to 1000 - fold [11].

The temperature of investigated object is unlimited and could range from one Kelvin degree to thousand Celsius degrees. In this case, it is possible to register the defects in moving objects, exposed to unwanted acoustic noises, even those defects which could have occurred some time ago. The above-described and registered distinctive properties in experiments, as well as, interaction-free detection method for desired signals proved the undeniable advantage of the advanced method- non-destructive testing method.

2. EXPERIMENT DATA AND RESULTS

It is a well-known fact that the application of microwave in testing metal surface uniformity is widespread [6, 8]. Surface defects, as cracks, can be detected through open-ended wave guide scanning by wave-types TM, TE and TEM. Operating distance to the surface is not more than several millimeters, while wave guide size is not more than 1 millimeters in diameter. Crack size is comparable to 1/4 of radiation wave length (i.e. at 100GHz, crack width is 0.15 - 0.2 mm.). Scanning time involves 2.78 hrs./cm2• at the speed of 100 micron/sec. Such scanning rate is effective only in the case of micro-surface diagnostics, which, in its turn, includes several mm2• Application of Doppler radar in detecting metal defects is an unknown innovative approach.

Radar based on Doppler effect is a well-known fact [12]. The object moving from the radiation source or to the radiation source modifies the reflected wave length by Δf

$\Delta f = 2\, v/\lambda = 2\, fv/C = 2f\, v/C$, where v - object speed; C - speed of light = 3 10^8m/sec; f falling wave, frequency = 10 10^9 - 37 10^9 Hz

Tuned radar to lateral components of a reflected modulated signal generate the motion speed of the object itself. Such a radar is called Doppler.

If the object is subjected to mechanical vibrations with frequency f_{var}, the Doppler radar output signal indicates spectral component equal to this frequency. An example could be a rotary disc (rotation axis is vertical), where a reflecting object is mounted on the edge and which is always directed towards the generator of incident waves-reflex receiver (generator-receiver located horizontally). In the case of angular rotation speed $\omega_{\mathrm{var}} = 2\pi n$ (radian/second), the radar would generate frequency f_{var}, = n (revolution /second). Ideally, the reflection coefficient of the object ρ directed towards transmit-receive can be written in:

$$\rho = \rho_0 \cdot exp^{j\,\omega_{\mathrm{var}}\,t\,\mathrm{A}} \tag{1}$$

where, ρ_0- reflection coefficient module (insignificant dependence on distance); *A*-coefficient approximately 1, depending on conductivity of reflected surface*;* *t* - time (seconds). However, arises the question- why the variable surface conductivity initiates emerging lateral components in the reflected signal spectral? In this case, it should be noted that the microwave field reflection coefficient p (vector variable) [13] depends on conductivity a (1/second), incident wave frequency ω (radian/second) and diaelectric conductivity of this metal $\varepsilon(\omega\sigma) = \varepsilon + j4\pi\,\sigma/\omega$, where, $\varepsilon-$ real part of conductivity (100-10000).

$$\rho = (\varepsilon^{1/2}(\omega,\ \sigma) - 1) / (\varepsilon^{1/2}(\omega,\ \sigma) + 1) \quad (2)$$

$\sqrt{\varepsilon(\omega,\sigma)} = +\sqrt{\mathrm{mod}(\varepsilon(\omega,\sigma))}\exp(\varphi(\varepsilon(\omega,\sigma))/2$, negative square root is excluded,

$$\mathrm{mod}(\varepsilon(\omega,\sigma)) = \sqrt{\varepsilon_l^2 + (2\sigma/f)^2} = A,\ f = \omega/2\pi,$$

$$\varphi(\varepsilon(\omega,\sigma)) = \arctan(2\sigma/(\varepsilon_l f)) = 2B,$$

$$\rho = ((\cos(B) - 1/\sqrt{A}) + j\sin(B))/\ ((\cos(B) + 1/\sqrt{A}) + j\sin(B)) \text{ at } \sqrt{A} \triangleright 0 \quad (3)$$

The imaginary part ratio $\varphi(\rho)$, determining the wave reflection phase, is of special interest:

$$\varphi(\rho) = \arctan(\sin(B)/(\cos(B) - 1/\sqrt{A})) - \arctan(\sin(B)/(\cos(B) + 1/\sqrt{A})) \quad (4)$$

The above-described calculations are applied only in the case if conductivity is a parameter for the total metal object. It is a well-known fact that the so-called "skin layer" has an essential role for metals. This is a thin metal surface layer within which the reflection process occurs. Generally speaking, not the total layer thickness but only a fraction of it, i.e. 1/1 0 is of profound importance. Namely, it is here that 90% of incident energy is reflected. Therefore, surface conductivity (conductivity of thin metal surface layer) could be that assigned parameter in calculations. The author's calculation showed that in the case when the real part of diaelectric conductivity = 100 ($2\sigma/f$) relation varies from 10-20%, reflection coefficient module changes slightly whereas the phase changes linear to conductivity change from 0-20%. $(2\sigma/f)$, In view of the experiment results, surface conductivity changes proportional to ultrasonic power output level and according to its frequency. Thus, we can rewrite the quation (2) for small changes in surface conductivity *B (σ).*

$$\rho \approx \rho_0 \cdot exp^{j2\pi ftB(\sigma)} \quad (5)$$

where, ρ_0- reflection coefficient module; *f* - ultrasonic frequency (Hz), *B(σ)* - coefficient of ultrasonic effect on surface conductivity (relative full conductivity *σ*); *t* - time (second). From a mathematical point of view the variable surface conductivity is complete analog to the moving surface as seen in (1) and (5). Thus, having focused Doppler radar on the reflecting metal surface with variable conductivity (for example, heating and cooling by known and fixed frequency) the spectral components (lateral components) of heating-cooling frequency could be observed in the spectrum of reflected signal. The calculations showed that the changing conductivity of up to a few percent is likely to further the emerging of spectral components up to 15-20 decibel, which, in its turn is higher than instrumental (thermal) noise under ambient environment temperature of 300ºK [5]. Heating is not the only means in changing surface conductivity. As stated above, the principle of the discovered phenomenon is changing the surface conductivity of a metal surface when exposed to ultrasonics. At a ultrasonic level of 5-10 W/cm^2 a measured level of spectral components was found within the range of 3-8 decibels above noise level. A locomotive wheel rim sample with an induced crack of 25mm in length and 6.5mm in width was tested. The induced crack was produced with the help of a propyl abrasive disc-like wheel (thickness- 4mm and depth-15mm.), which was subjected to mechanical shock to form the crack itself (without splitting the outermost edge) (Fig. 1).

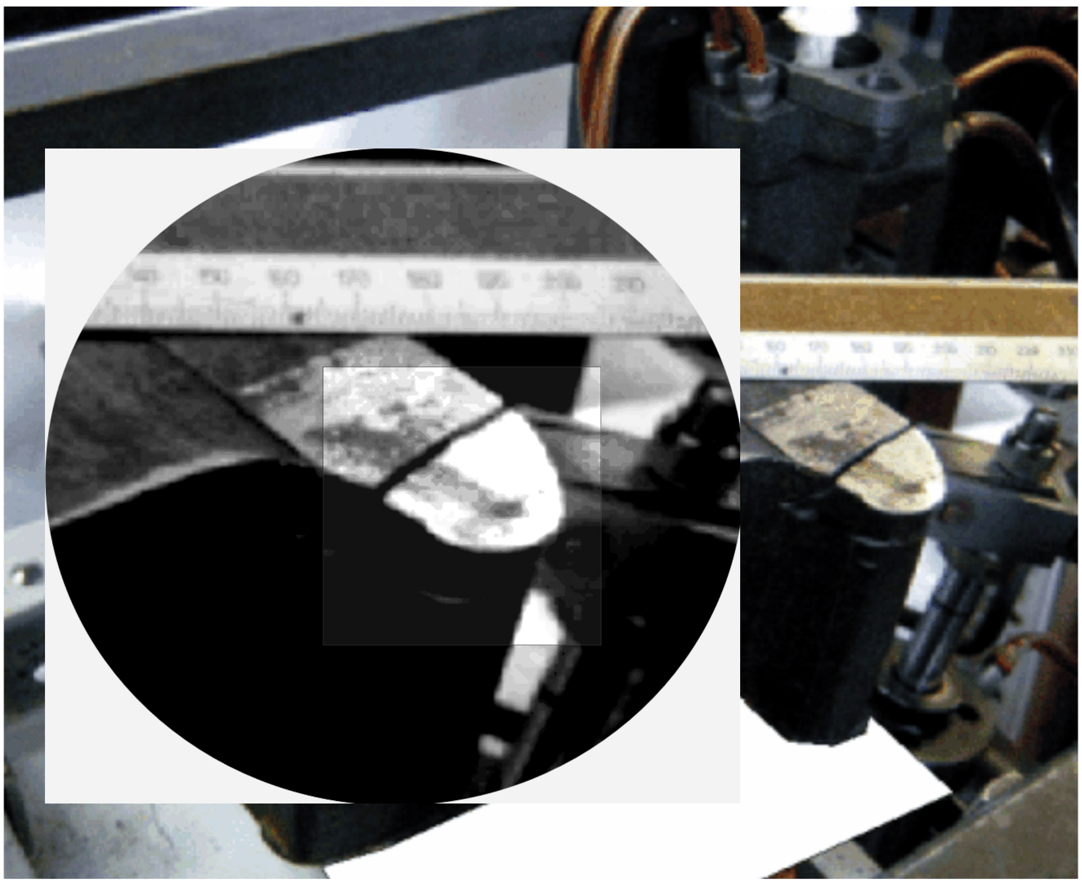

Fig. 1. A locomotive wheel rim sample with an induced crack of 25mm in length and 6.5mm depth

Measuring the spectral ultrasonic component level at the outlet of the microwave sensor was conducted before and after the crack emerged. Desired signal at the outlet of the microwave sensor (Doppler radar) did not exceed the noise level existing before the emerging defect but this noise level from 5 to 8 decibels arose instantly after the crack emerged. It should be noted that the level of the desired signal was changing, i.e. during 20-25 seconds it was stable, then decreased rapidly while fading away for 1-2 seconds and finally emerging again. This" flickering" pattern of the desired signal continued for 3-5 minutes, declining downwards to zero. At this point it was impossible to register the signal. The experiment involved other types of cracks within one and the same locomotive wheel rim, as well as cracks on the rib of a whole railway wheel. This experiment was conducted in Novosibirsk Technology Institute of Research Instrument Engineering, SO RAS. This research was conducted within the framework of the Federal Program "START-10". A group of experts from Technology Institute of Research Instrument Engineering, SO RAS registered such results that were as low as reasonably practicable in comparison to the above-stated results.

Based on S. Brichkov's method, it was possible for the first time ever to activate (reactivate) a desired signal. Heating up the crack area to 100-300ºC and further water cooling resulted in regaining the level of the desired signal (5-8 decibels). Then the following repeated: " flickering" pattern of signal level changing and complete fading effect in 2-3 minutes. It was possible to reactivate "old" cracks in several days after their occurrence. At present experiments are being conducted on different metal samples (steel, copper, aluminum, brass, lead), the target of which is to investigate the possibilities of generating (registering, determining) the level of a desired signal and its" flickering" pattern during the fading effect.

3. CONCLUSION

The above-described experiment data proves the novel of this non-destructive testing method. At the same time it should be highlighted that the application of radar as a microwave sensor for defects would probably firmly establish itself in time among already existing methods. The faster the implementation, the less dangerous occurrences of metal object failure. Unfortunately, this discovery has not obtained the widest possible support within Russian developed economic sectors, including railway transportation, thermal energy, machine tool engineering and aircraft engineering. However, the sole exception was the Federal Program grant "START-I 0." We render our thanks to S.Y. Plotnikov for his invaluable assistance in conducting these testings. It should be noted, that the major part of the research was financed by the Federal Program for small enterprises "START-1 0." At the 2nd International Conference in Tomsk (Feburary, 2011), German experts from Fraunhoferr Institut fUr Produktionsanlagen und Konstruktionstechnik IPK (Produktionstechnisches Zentrum / PTZ) became interested in this research. Based on further cooperation, joint testings were conducted (May, 2012), as well as temporal provision of the equipment kit RIAD-2 for conducting experiments on samples in Berlin. The experiments in May were successful. Such research has become possible nowadays. Published research results should be of great interest for different specialists.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Ahmed S, Saka M. Quantitative nondestructive testing of small, tight cracks using ultrasonic angle beam technique. Materials Evaluation. 2000;58(4):564-74.
2. NDE of Closed Fatigue Crack on the Metal Surface by Microwaves Ed. Ju Y, M. Saka, D. Luo Department of Mechanical Engineering, Tohoku University, Aoba 01, Aramaki, Aoba-ku, Sendai Japan. 2000;980-8579:2-4.
3. So K, Sinclair A. Size measurement of tightly closed surface cracks by surface acoustic waves. Nondestructive Testing Communication. 1987;3(3):67-74.

4. Gorbunov V, Sutorikhin V. Possible control of elastic deformation limits by the microwave (MW) method. Defectoscopy. 1999;7:75-80.
5. Sutorikhin V. Sophisticated Microwave Nondestructive Testing Method for Metals. Applied Physics Research. 2012;4(4-10):8-10.
6. Ghodgaonkar DK, Hj Hamzah. Microwave nondestructive testing of coatings and paints using free-space microwave measurement system, Browse Conference Publications > Telecommunication Technology, Published in: Telecommunication Technology. 2003;71.
7. Kerouedan J, Queffelec P. Detection of micro-cracks on metal surfaces using near-field microwave dual-behavior resonator filters. Measurement Science and Technology. 2008;19(10):54.
8. Kim Y, Jofre L, DFF, FMQ. "Microwave sub-surface imaging technology for damage detection of concrete structures," Journal of Engineering Mechanics, SCE 130; 2004.
9. Gorbunov VI, Sutorihin VA. Possibility defectoscope of the metal details of the microwave oven afield. Electronic magazine "Technical acoustics". 2010;60-66.
10. Vasilyev YD, Lyuboshitz VL. The virial Theorem and some properties of the electron gas in metals (Session RAS 23.02.1994 g.). The Successes of the Physical Sciences. 1994;4(164):367-374.
11. Golitsin BB. Selecta Academy of Science. USSR: Moscow. 1960;1:95.
12. Radar Doppler. Available: http://ebookbrowsee.net/radardoppler-pdf-d42938755
13. Leontovich MA. Approximate boundary conditions for electromagnetic fields on surfaces of well-conductive bodies. Research in Radio-wave Propagation; 1948.

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