Aircraft Wheel Testing with Remote Eddy Current Technique using a HTS SQUID Magnetometer

Rainer Hohmann, Dieter Lomparski, Hans-Joachim Krause, Marc v. Kreutzbruck, and Willi Becker

Abstract— **An aircraft wheel testing system using a planar HTS SQUID gradiometer with Joule-Thomson machine cooling in conjunction with a differential eddy current (EC) excitation has recently been developed [1]. From a routine performance test in the wheel testing facility at the Lufthansa Base, Frankfurt/M. airport, we learned that the quadrupolar flaw signatures complicate signal interpretation considerably. In order to overcome these difficulties, the system was equipped with a HTS rf magnetometer SQUID sensor and an absolute EC excitation coil. The coil was mounted with a lateral displacement with respect to the SQUID. The geometry was chosen similar to the remote EC technique: a given point on the rotating wheel first passes underneath the excitation coil and then underneath the sensor. We analyzed the dependence of the response field of an inside crack on excitation coil displacement, EC frequency and lock-in phase angle and found an optimum rotation velocity for deep lying defects. The depth selectivity of the technique is discussed.**

Index Terms—**Aircraft, Eddy Current, Nondestructive Testing, SQUIDs.**

I. INTRODUCTION

Aircraft wheels are subject to enormous stress and braking-generated heat during take-off and landing. Because of the concentration of mechanical and thermal stress, hidden cracks emanate preferably next to the steel keys where the brake pulleys are fastened to the rim, see Fig. 1. The cracks are not visible from the inside of the wheels because they are covered by heat shields. Today, the wheels are tested with conventional low-frequency eddy current (EC) from the outside. On a semi-automated system, a circumferential scan measurement is performed after taking off the tires. Deep flaws are detected with a low frequency eddy current probe. However, the sensitivity is limited to large flaws: flaws with 40% wall penetration from the inside and a length twice the wall thickness can be identified reliably. In order to safely detect small hidden flaws, the wheel has to be disassembled and be tested from the inside. With manual ultrasonic testing, very small flaws may be found. This procedure, however, is very tedious. Gel or water has to be used in order to couple the ultrasonic waves into the wheel. Success and reliability strongly depend on the inspector's skills. Therefore, aircraft operators such as Lufthansa are very interested in a reliable, automated testing technique working from the outside. Lufthansa's specification include a total time of 4 min for mounting the wheel on the stand, testing it and evaluating the measurement. For the minimum flaw size to be detected, 10% was specified, meaning that the flaw penetrates the wheel body by 10% from the inside, leaving an intact 90% of the wall thickness remaining.

Due to their unsurpassed dynamic range, SQUIDs are very well suited to serve as sensitive magnetic field sensors in eddy current nondestructive evaluation (NDE) [1]-[4]. A German research collaboration (Rohmann GmbH, ILK Dresden, University of Gießen, Forschungszentrum Jülich, EADS Airbus, and Lufthansa) is working on the introduction of HTS SQUIDs into aircraft testing. We have previously shown that a rf SQUID system including a Joule-Thomson refrigerator can be used for eddy current testing of aircraft wheels [1]. In the present paper, we report on the setup and performance of an automated system for wheel inspection, using a HTS rf planar gradiometer or magnetometer SQUID on a Joule-Thomson cryocooler [5]. Two different configurations are presented: first, a planar HTS rf double hole gradiometer is utilized in conjunction with a differential excitation. The second configuration, using an HTS rf washer magnetometer in conjunction with an absolute excitation, is motivated by the

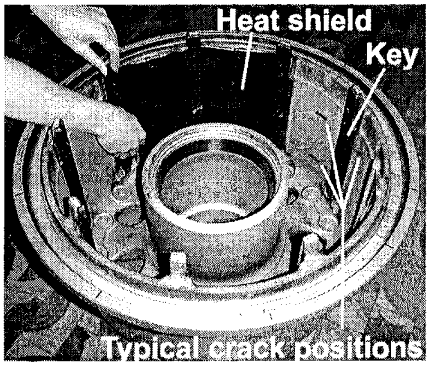

Fig. 1. Photograph of an Boeing 747 aircraft wheel rim. Typical position of inside cracks next to keys are indicated. They are not accessible from the inside because of the heat shields (some are removed for the photo).

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remote eddy current technique in conventional eddy current testing. The performance of the two schemes in the detection of very small inside flaws is compared.

II. SETUP WITH DIFFERENTIAL EXCITATION AND READOUT

A. *SQUIDs and Electronics*

In the differential setup, we use a planar HTS rf double hole gradiometer [6] as SQUID sensor. The baseline is 3.6 mm and the gradient-to-flux coefficient is 15.7 nT/($\Phi_0$cm). The SQUID is operated in flux-locked loop with an rf SQUID electronics V3.0 available from JSQ [7]. The frequency of the rf tank circuit is approximately 900 MHz. The voltage-to-flux coefficient is about 8 mV/Φ_0, yielding a maximum dynamic range of $\pm 1250\,\Phi_0$. This dynamic range is sufficient even in the case of magnetized keys. The SQUID could be operated without any shielding even in strongly disturbed environments.

B. *Eddy current excitation*

For the generation of eddy currents in the sample, a double-D configuration of induction coils is used [8],[9]. This configuration approximately cancels the excitation field at the SQUID's sensing location. Fig. 2 shows schematically the configuration of excitation coil and SQUID gradiometer.

C. *Joule-Thomson machine cooling*

SQUID cooling is performed on the basis of a commercially available closed-cycle Joule-Thomson cooler (Cryotiger® from APD). The cooler was modified in order to be applicable for high-sensitivity magnetic field measurements [5]. Plastic gas lines are used, making the cold head easy to move and handle. Vibration reduction and electromagnetic interference suppression are implemented. A sapphire rod is used to thermally couple the SQUID while serving as an electrical isolation, see Fig. 3. In addition to these measures described elsewhere [5], we introduced a vacuum housing fabricated from titanium alloy (thickness 0.5 to 1 mm). This enclosure not only improves mechanical stability and the vacuum hold time (compared to the previously used fiberglass), it also serves as a electromagnetic shield for environmental disturbances above 1 kHz. As the eddy current frequencies used for wheel testing typically vary from 100 to 300 Hz, signals pass this housing almost undamped.

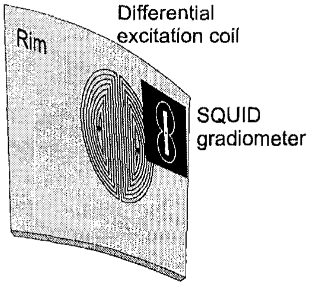

Fig. 2. Configuration with differential excitation and readout: a planar double D excitation coil is placed in front of the SQUID gradiometer.

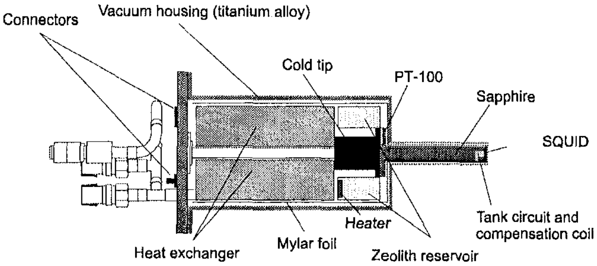

Fig. 3. Scheme of the modified Joule-Thomson cold head. A sapphire rod carrying the SQUID is mounted on the copper cold plate. The cold head is enclosed by a vacuum housing fabricated from titanium alloy.

D. *Wheel testing unit*

Fig. 4 shows the main parts of the wheel testing unit. It contains a rotating table for the aircraft wheels and a robot holding the sensor head. In addition, a lock-in amplifier (Stanford Research, SR830) and a computer for data acquisition and signal analysis are integrated into a computer rack. While the wheel is rotating with a frequency of about 0.25 Hz, the robot moves the cryostat along the outer contour, parallel to wheel's axis. The data acquisition system stores both the in-phase and quadrature component of the lock-in signal. Thus, the lock-in detection phase may be rotated arbitrarily after scanning. One obtains a two dimensional plot, with the rotation angle on the x-axis and the position of the sensor head on the y-axis (a mapping the wheel surface).

III. WHEEL MEASUREMENT CAMPAIGN

During a three-day measurement campaign at the Lufthansa base at Frankfurt/M. airport, we thoroughly tested our SQUID system for wheel inspection. A total of 45 aircraft wheel measurements were carried out. Stable and reliable SQUID operation was demonstrated.

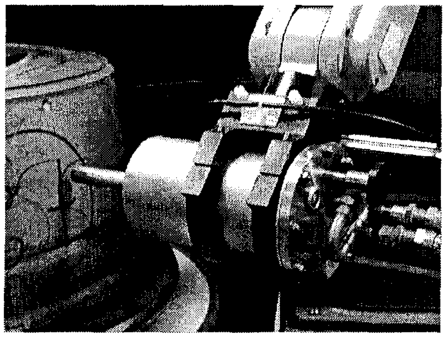

Fig. 4. Photograph of the SQUID head of the wheel testing system. While the aircraft wheel rim is rotating, the Joule-Thomson cold head with the SQUID at the tip is moved down the wheel's contour by the robot.

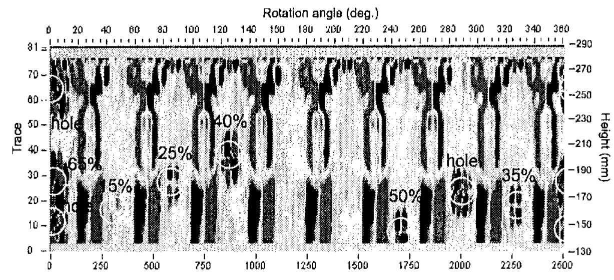

Fig. 5. Measurement of our calibration wheel (Boeing 747). A number of sawcuts with a wall penetration indicated by the percentages (ranging from 15% to 65%) have been cut into the wheel from the inside, in order to have well-defined flaws. The gradiometer SQUID measurement with differential excitation yields quadrupolar signatures of the flaws. Additional signals are received from the nine vertical keys (the regularly shaped vertical stripes) and from three holes in the wheel body.

Fig. 5 shows a measurement of our calibration wheel. Our reference sawcuts (15%, 25%, 35%, 50%, 65%) are all detected clearly. Fig. 6 shows a measurement of an Airbus A300-600 wheel. We found a crack at the key which hadn't be found during the previous conventional eddy current test.

However, from our measurements and from discussions with inspectors, we concluded that the quadrupolar flaw signatures complicate signal interpretation considerably. Motivated by the remote eddy current scheme of conventional eddy current testing, we modified our system in order to overcome these difficulties.

IV. SETUP WITH REMOTE EDDY CURRENT EXCITATION

The remote eddy current technique comprises of an absolute excitation coil and an absolute detection coil [10]. In our remote EC setup, we use an HTS rf washer SQUID magnetometer [7] as SQUID sensor. The washer diameter is 2.5 mm and the field-to-flux coefficient is 15 nT/Φ_0. With a V3.0 SQUID electronics equipped with a video output driver, a voltage-to-flux coefficient of about 4 mV/Φ_0 was achieved. The dynamic range of $\pm 2500\ \Phi_0$ corresponds to $\pm 37.5\ \mu$T, which is sufficient for the movement the SQUID undergoes during scanning a wheel contour (an 80° rotation in the Earth's magnetic field). However, in the case of strongly magnetized keys, the dynamic range is not sufficient. Therefore, some wheels may only be tested after dismantling the keys. It was no problem to operate the SQUID in disturbed environments.

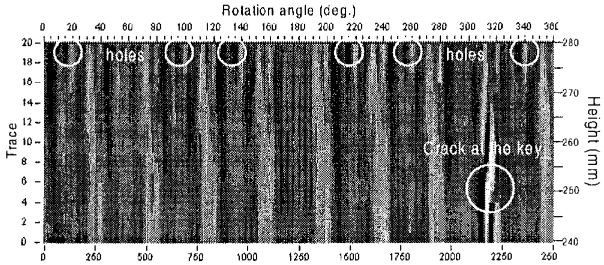

Fig. 6. Gradiometer (double differential) SQUID measurement of an Airbus A300-600 wheel at Frankfurt airport. The circle marks a crack at the key.

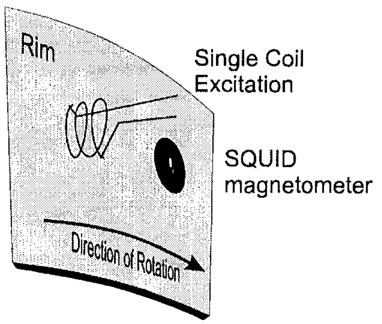

Fig. 7. Configuration with remote eddy current excitation and readout: an absolute excitation coil is placed adjacent to the SQUID magnetometer.

For excitation of the eddy currents, a standard solenoid coil from Rohmann GmbH was used. The coil is wound on a ferrite cup core, yielding field focussing into the sample [10]. The coil is mounted with a lateral displacement with respect to the SQUID. In remote eddy current, exciter and sensor are spaced in the direction of the sample movement. A given point on the rotating wheel first passes the coil and then reaches the SQUID sensor. Eddy current testing may be visualized as a diffusive propagation of the excitation into the material, scattering at the flaw and diffusion of the scattered wavefront to the sensor. It becomes obvious that the eddy current is dragged towards the sensor by the movement of the sample. This effect is well known as drag effect in conventional eddy current testing [10].

We analyzed the dependence of the response field of an inside crack on excitation coil displacement, EC frequency and lock-in phase angle and found that maximum flaw signal for deep lying defects depends on flaw depth and rotation velocity, see Fig. 8. Deep flaws are best detected with slow rotation velocities, shallow flaws with fast. Thus, the remote eddy current technique yields increased sensitivity (compared to surface flaws) for a chosen depth range, in case the coil-to-SQUID distance and the angular velocity of the wheel are adjusted properly. Thus, additional depth selectivity is gained. Of course, the proper adjustment of the lock-in phase also gives depth selectivity, as discussed in Refs. [3],[11].

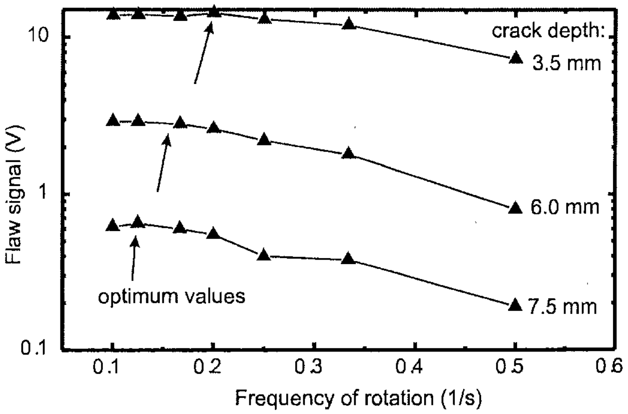

Fig. 8. Crack signal as a function of angular rotation velocity of the wheel, for three different flaw depths. Different optimum velocities are found.

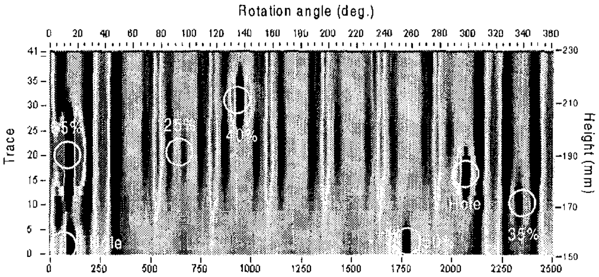

Fig. 9. Measurement of our calibration wheel (Boeing 747), using the remote eddy current scheme. The magnetometer SQUID measurement with absolute excitation yields absolute signatures of the flaws. The sawcuts can much more easily be identified among the signals from the nine vertical keys (the regularly shaped vertical stripes) and the three holes. In comparison to the double-differential scheme measurement of the same wheel (Fig. 5), this eddy current map is much easier to evaluate.

V. WHEEL MEASUREMENTS WITH REMOTE EDDY CURRENT

In order to check the performance of the remote EC scheme in comparison to the previously used double differential scheme, we measured our calibration wheel, see Fig. 9. The artificial flaws appear much more pronounced than in Fig. 5. Scans appear nicer to the inspector's eyes.

We also measured a reference wheel provided by Rohmann GmbH, a Boeing 737 wheel with three sawcuts, penetrating the wall from the inside by 30%, 20%, and 10%, respectively. In addition, the wheel contains a natural fatigue crack, which was verified by manual ultrasonic testing. Fig. 10 shows a trace measured on that wheel with the SQUID in conjunction with remote eddy current. All flaws, including the 10% flaw, are clearly detected among the strong signals from the seven keys. From the comparison of signal amplitudes, one can conclude that the fatigue crack is comparable in size to the 30% sawcut.

VI. CONCLUSION

An automated eddy current testing system for aircraft wheel rims was developed, using an HTS SQUID sensor with Joule-Thomson machine cooling mounted on a robot. A 3-day measurement campaign at the wheel testing facility at the Lufthansa Base, Frankfurt/M. airport proved the reliability and stability of operation in strongly disturbed environment. It turned out that the quadrupolar flaw signatures complicate signal interpretation considerably. In order to overcome these difficulties, a remote eddy current excitation and detection scheme was adopted. The system was equipped with a HTS rf magnetometer SQUID sensor and an absolute excitation coil, mounted with a lateral displacement with respect to the SQUID. Analysis of the response field of an inside crack as a function of excitation coil displacement, eddy current frequency and lock-in phase angle yielded an optimum rotation velocity for deep lying defects. The technique yields depth selectivity: signals from deep flaws are enhanced over surface flaws. Tests were conducted on aircraft wheels with known flaws. On a Boeing 737 wheel, an inner flaw penetrating only 10% of the wall thickness was detected by scanning the outside surface of the rim. Thus, Lufthansa's specification was reached for the first time. Future work will direct towards improving reliability of operation, signal analysis and eventually commercialization of the system.

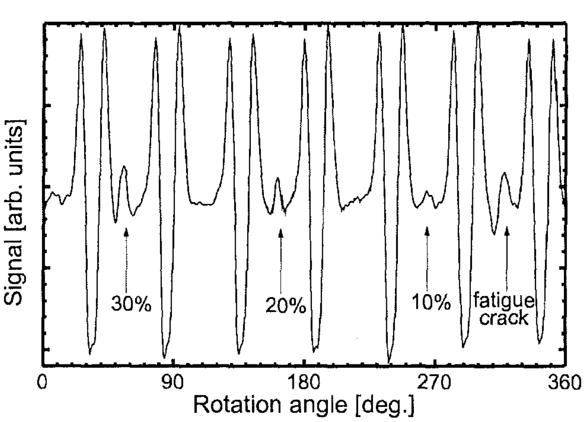

Fig. 10. Single trace measured on a Boeing 737 wheel, using the remote eddy current scheme. The three sawcuts with 30%, 20%, and 10% wall penetration are easily identified among the signals from the seven keys.

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