

## Phased matched guided wave excitation for ultrasonic thermography

by M. Rahammer\*, I. Solodov\*, W. Bisle\*\*, D. Scherling\*\* and M. Kreuzbruck\*

\* Institut für Kunststofftechnik, University of Stuttgart, Pfaffenwaldring 32, 70569 Stuttgart, Germany, markus.rahammer@ikt.uni-stuttgart.de

\*\* Airbus Operations GmbH, ESCMN3, Airbus-Allee 1, 28199 Bremen, Germany

### Abstract

Ultrasonic thermographic testing (UTT), also known as thermosonics or vibrothermography, is an established NDT method praised for its full-field and defect-selective imaging. The concept of local defect resonance is known to improve energy efficiency in defect activation during UTT. In this paper, we present an innovative, patented coupling method that significantly improves the distribution of ultrasonic energy of guided waves within the specimen. This is achieved with the help of a phased matched excitation source. The additional improvement results in an increase of the defect vibration amplitude and the following thermal signal while using low energy input sources.

### 1. Introduction

With the growing demand for composite materials in the aviation and automotive industries comes the need for fast and simple-to-use non-destructive testing methods for detection of life-cycle defects. One of industry's major requirements for integrating new NDT methods into their in-service environment of composite structures is usability by untrained personnel. I.e. the testing must be simple to perform and the results easy to evaluate. Furthermore, the test set-up has to be small and light as well as robust enough to be applied in the field, e.g. in a service hangar or garage. There are several contenders available that claim to provide a fast and mobile detection of impact damage-related delaminations. However, those based on ultrasonic testing are too complicated for untrained personnel and the results can only be evaluated for known materials and geometries. Those based on optically excited thermography suffer from low depth resolution and difficult-to-interpret results.

One potential NDT method that can detect impact damage unambiguously is ultrasonic thermography, because it is a so-called dark field method. A thermal response will only occur when a defect is present. Due to the low efficient mechanisms involved, ultrasonic thermography is currently only used with bulky high power equipment. In order to advance this method from its current lab status to a reliable field-ready device a reduction in energy consumption and improved defect activation is necessary. Only then can the heavy generators and transducers be exchanged for smaller equipment. One way to achieve this goal is the combination of ultrasonic thermography with the concept of LDR. In this paper, a method is presented that further enhances the channelling of ultrasound from the source to the defect.

### 2. State of the Art

The research described in this paper was performed to further enhance the efficiency in channelling ultrasonic power directly into the testing area and the potential defect, respectively. For these investigations we utilize two non-destructive testing techniques, namely laser vibrometry and thermography for visualizing the effects of local defect resonances and the improvements made thereto.

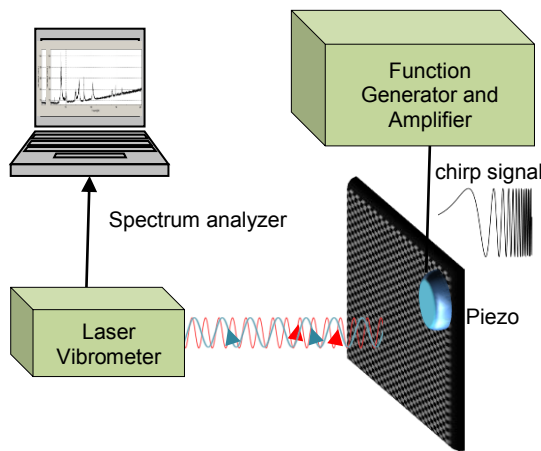
#### 2.1. Local Defect Resonance

The concept of LDR has been first investigated and described in [1, 2]. Local defect resonances occur on the basis that inclusion of a defect leads to a local decrease in stiffness for a certain mass of the material in this area. By utilizing a frequency match of the driving ultrasonic source and the resonance frequency of the local defect area, a very efficient energy pumping into the defect area is possible. This results in high amplifications of the defect vibration amplitude as compared to the residual sound specimen area. Analytical estimations have been performed for simple flat bottom holes [2] to predict defect resonance frequencies for simple defect shapes, that are in theory similar to delaminations in composites. Practical applications to detect real defects in composite material have been demonstrated in [3]. Recent contributions of other groups in the subject demonstrated the benefit of LDR for inspection of delaminations [4] and kissing bonds [5].

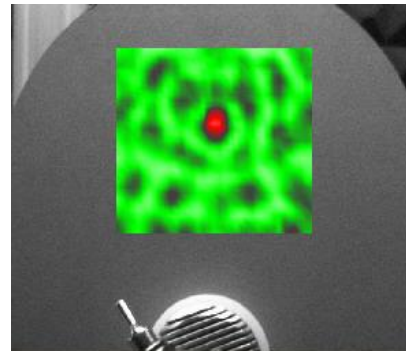
Due to the high efficiency that LDR can provide, a low input power ( $< 1$  W electrical power) is necessary to activate the defects. This opens up applications with inexpensive excitation sources, e.g. simple piezo disc transducers, or very flexible solutions like vacuum attached piezo shakers.

In order to visualize LDR, the most applicable tool used is laser scanning vibrometry. A laser Doppler vibrometer records the vibration velocities for a given bandwidth in a selected area over the specimen's surface (see Fig. 1). Frequency-selective visualization is performed by plotting local vibration amplitudes vs. the scanning coordinates. As

shown in **Fig. 2**, vibration velocity amplitudes are colour coded from green (low) to red (high). The LDR at this impact damage in CFRP is clearly seen due to its high relative vibration amplitude.



**Fig. 1.** Schematics of vibrometry test set-up

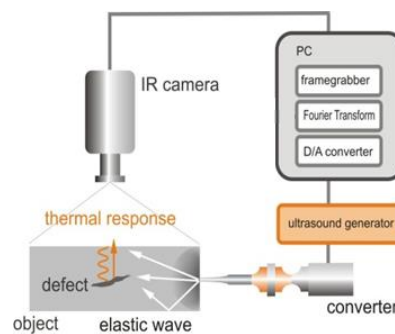


**Fig. 2.** Local Defect Resonance in CFRP for vacuum attached transducer excitation

Other methods of visualizing local defect resonances include interferometric techniques (e.g. shearography) and thermal techniques (e.g. ultrasonic thermography) [3].

## 2.2. Basics of ultrasonic thermography coupled with LDR

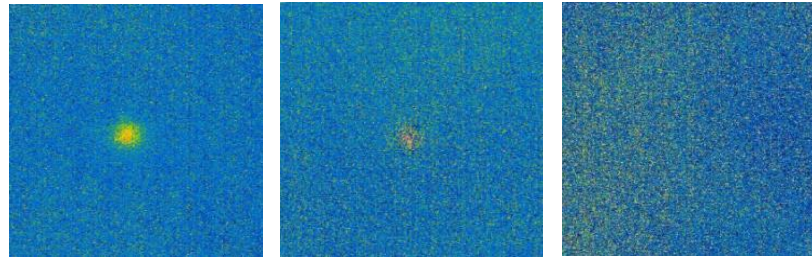
Ultrasonic thermography, also known as acoustic thermography [6], ultrasound excited thermography [7], sonic IR [8] or thermosonics [9], is a well-established NDT technique mainly used for finding cracks in various materials. Its main advantage is the fast and simple employment coupled with an unambiguous measurement result. As shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**, a specimen is activated by ultrasound, usually generated by means of a high power ultrasonic welding device. Frictional heating, later described as external friction, at the crack tip produces enough heat to be detected via an IR-camera at the specimen surface.



**Fig. 3.** Standard ultrasonic thermography setup

While Coulomb friction is a prominent heating mechanism and has long been described [10], another mechanism, namely damping or internal friction, can also lead to measurable temperature changes [11]. Internal friction heating resulting from ultrasonic activation mainly occurs where strain is the highest. Because in-plane strain is related to the first derivative of displacement, thermal vibration patterns are akin but not equal to displacement distributions. This was used by [12] to reproduce vibration patterns similar to well-known Chladni figures with an IR-camera.

Recent progress has shown that the employment of high power ultrasonic equipment is not necessary, when the aforementioned principle of LDR is incorporated [3, 13]. Low input powers are necessary in order to activate the defect and produce vibration amplitudes high enough for measuring heat. Fig. 4 illustrates the effect of LDR on the thermal defect response in an impact damaged CFRP specimen. The heating mechanism for impact damage is expected to be a combination of internal and external friction.



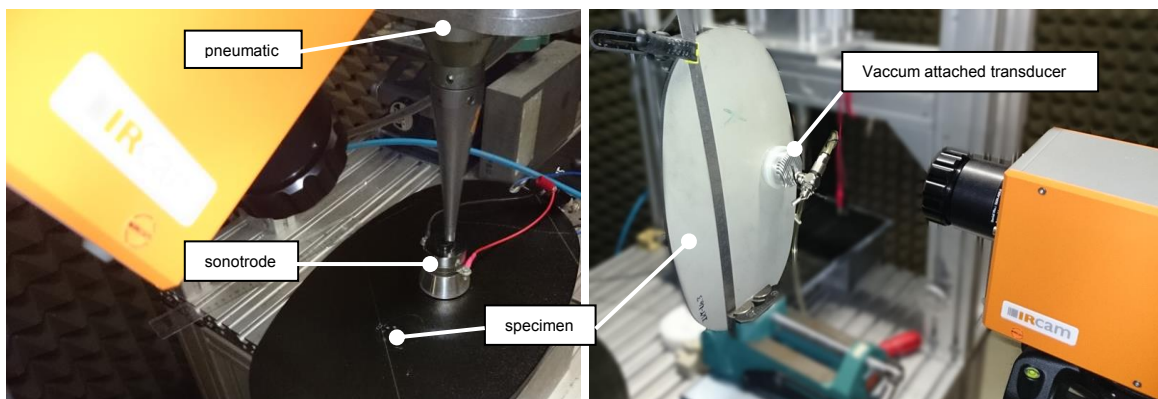
**Fig. 3.** LDR-thermography results for CFRP with impact damage. Excitation frequencies: 43 kHz (left), 46 kHz (middle), 49 kHz (right).

## 1. Experimental

### 3.1. Ultrasonic thermography set-up

The vibrometry and ultrasonic thermography results shown in this paper are obtained for low power ultrasonic excitation via either inexpensive ultrasonic cleaning sonotrodes or vacuum-attached transducer. Both are piezo-based and require input voltages between 10 and 60 V. Excitation signals were produced by standard frequency generators and amplifiers. The sonotrodes were pressed onto the specimen surface to improve coupling efficiency (see Fig. 4 (left)). The vacuum-attached transducer develops enough pressing force for the experiments (Fig. 4 (right)).

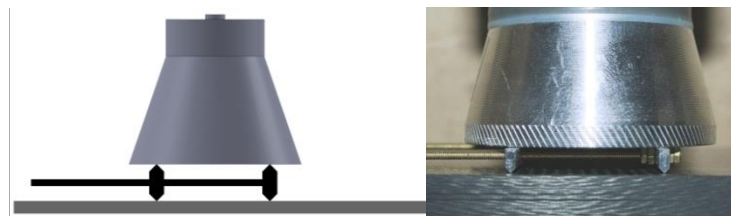
The IR-camera used is a cooled Equus 327M with 640x512 pixels and NETD <20 mK. Thermal signal processing is performed online by the software DisplayIMG of edevis GmbH. Typically pulse-phase Fourier transform of the recorded temperature data is performed in order to low-pass filter the signal and improve signal-to-noise ratio.



**Fig. 4.** LDR thermography test set-ups for sonotrode (left) and vacuum attached transducer (right) excitation

### 3.2. Phased matched guided wave excitation set-up and effects

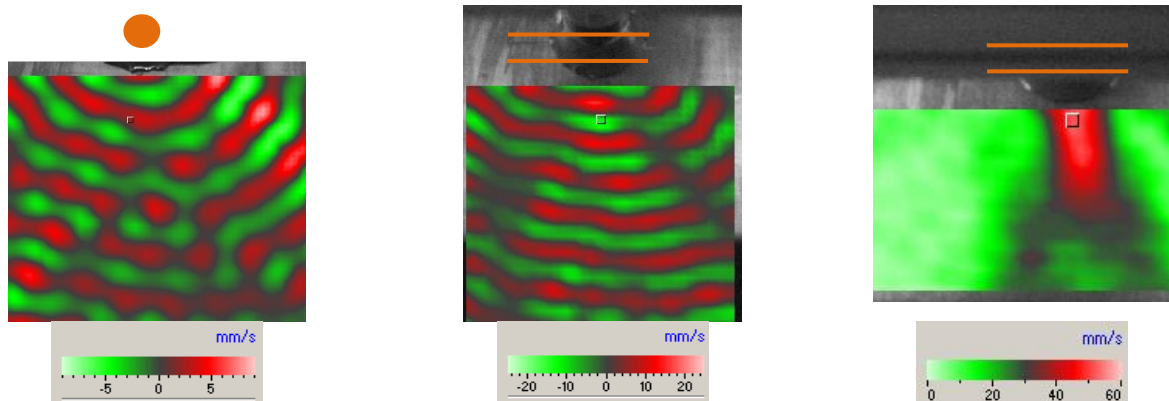
A device for enhancing plate wave amplitude was developed and patented. By placing 2.5D profiles, e.g. wires, between the excitation source and the specimen surface a directional guiding of the plate waves was achieved. This set-up is displayed in Fig. 5.



**Fig. 5.** Phased matched guided wave excitation: Schematics (left) and set-up photography (right).

Phase matching between the waves from the line contacts is achieved by adjusting their distance to the ultrasonic plate wave wavelength. The constructive interference of the plate waves generated by each of the two sources results in enhancement of the total plate wave amplitude perpendicular to the line contact and decreased amplitudes in all other directions, respectively. Furthermore the wave front propagates becomes a plane wave pattern. This can be seen in Fig. 6, where comparable measurements with a point-like contact (left) and the line-contact (center and right,

respectively) have been performed using the same input power and frequency. The vibration velocity amplitude for the line source is more than twice than before.



**Fig. 6.** Effect of phased matching on guided wave excitation: Cylindrical wave pattern for a point source (left), quasi-plane wave pattern (phased matched source, center) and RMS values of the quasi-plane wave field (right). Corresponding amplitude scales are beneath the measurement results.

The main advantage of this directing effect is the channelling of ultrasonic energy towards a specified area. As can be seen in **Fig. 6** (right), the vibration amplitude is significantly higher in the chosen direction. This is advantageous for methods like ultrasonic thermography where there is usually a field of view that does not incorporate all of the cylindrical area around the source but a smaller region of interest.

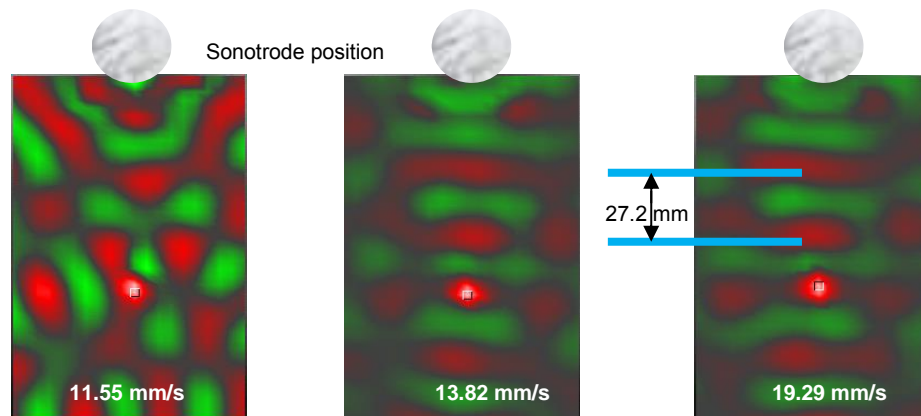
During the experiments, several types of line coupling profiles were investigated to improve the performance. Early versions used 1 mm copper wires attached to the sonotrode surface. Best results were obtained for an array of steel bars that were truncated on either one side (**Fig. 5**, right) or both sides (**Fig. 5**, left).

## 2. Results

Several experiments have been performed to investigate the viability of the phased matched excitation. The vibrometry and ultrasonic thermography results will confirm the positive effects of the plate wave guiding mechanism.

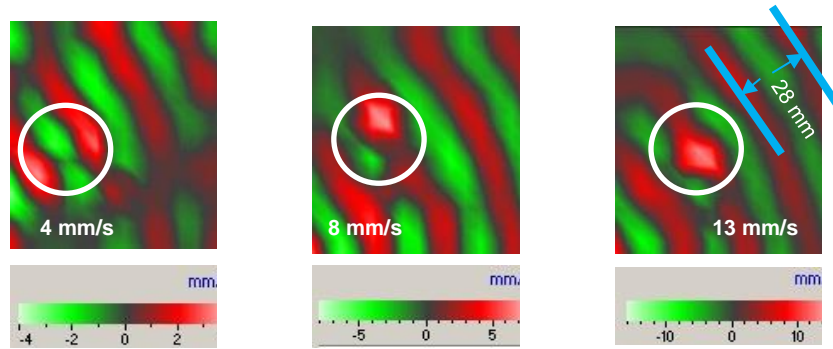
### 4.1. Quantification of phased matched guided wave excitation via laser vibrometry

First a CFRP plate with impact damage was investigated. One of the defect LDR frequencies was found around 43 kHz. As shown in **Fig. 7**, the maximum vibration velocity amplitude at the defect position measured for excitation by a sonotrode attached directly to the specimen surface approximately 50 mm away from the source is 11.55 mm/s. The amplitude is somewhat increased by placing wires between the sonotrode and the plate with a distance of 27.2 mm (ultrasonic wavelength for this material at 43 kHz). The increase by almost a factor two was achieved when using the single truncated steel bars. It is also worth noting, that the wave front and directivity improved substantially.



**Fig. 7.** Comparison of vibration amplitude at the defect (marked by a small transparent square). No couplant (left), 1 mm wires (middle) and steel bars (right) for an impact damage in CFRP.

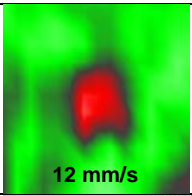
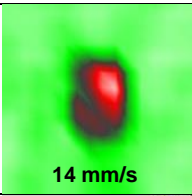
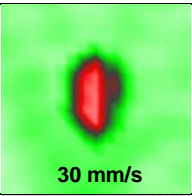
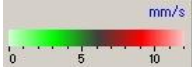
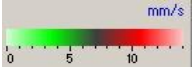
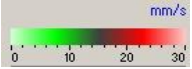
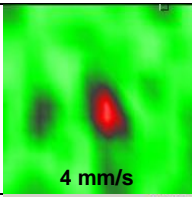
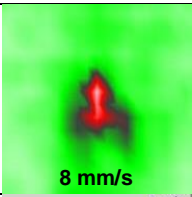
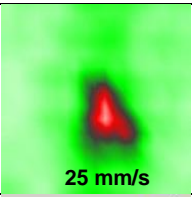

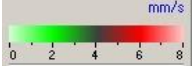
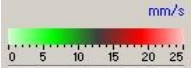
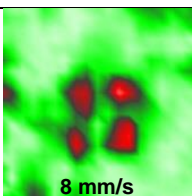
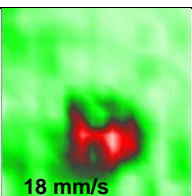
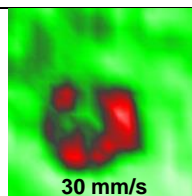


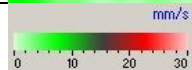
A similar experiment was performed for a CFRP plate with local heat damage with LDR frequency around 54 kHz. At this frequency, the ultrasonic wavelength in the specimen was measured to be 28 mm. As shown in **Fig. 8**, vibration amplitude increases from 4 mm/s to 8 mm/s when using wires and to 13 mm/s when using the single-truncated steel bars.



**Fig. 8.** Comparison of vibration amplitude at the defect by use of no couplant (left), 1 mm wires (middle) and steel bars (right) for heat damage in CFRP.

A few more experiments were performed for this particular defect at higher-order LDR frequencies. These results are compiled in Table 1 and indicate the amplitude enhancement in the defect area at each LDR frequency.

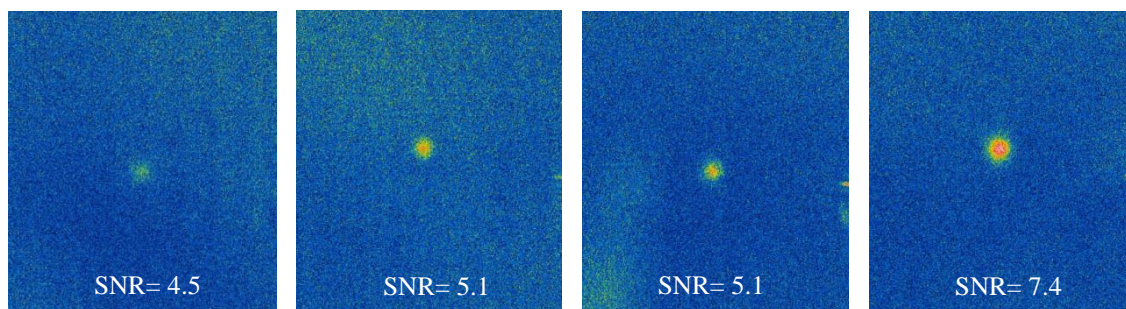
**Table 1.** Vibrometry results for various-order LDR frequencies.

LDR Frequency	Direct contact	Copper Wires	Single truncated steel bars	Dual truncated steel bars
33.14 kHz	 12 mm/s	 14 mm/s	 30 mm/s	
				
52.13 kHz	 4 mm/s	 8 mm/s	 25 mm/s	
				
66.39 kHz	 8 mm/s		 18 mm/s	 30 mm/s
				

#### 4.2. Enhancing ultrasonic thermography with phased matched guided wave excitation

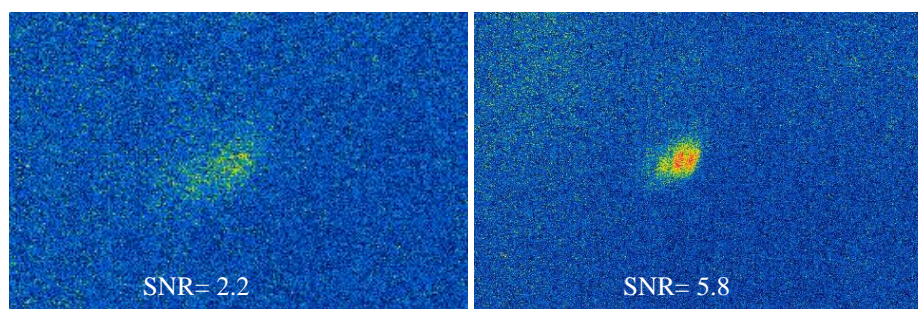
The positive effects of phased matching guided waves found by laser vibrometry measurements were applied to ultrasonic thermography experiments as well. Thermal response at the defect is proportional to the vibration amplitude and will hence profit from the newly developed method.

For the same specimen and parameters as shown in Fig. 7 ultrasonic thermography measurements have been performed. The results are illustrated in Fig. 9. The best quantitative way to evaluate the quality of thermosonic images is using signal-to-noise ratio, i.e. the ratio of the defect thermal output and the noise in the sound area. The application of phased matched guided wave excitation does improve the results in the same order of quantity as an increase in input power of 25%.



**Fig. 9.** LDR thermography results for impact damage in CFRP. From left to right: 40 V input, direct contact; 40 V input, wires; 50 V input, direct contact; 50 V input, wires.

Lastly thermography measurements have been performed for the heat damage CFRP specimen from Fig. 8. As expected, SNR was increased substantially by using phased matched guided wave excitation.



**Fig. 10.** LDR (54.11 kHz) Thermography results for heat damage in CFRP (cf. Fig. 8 for vibrometry results) with direct contact (left) and steel bar coupling (right).

### 3. Conclusion

A method for further enhancing the ultrasonic activation efficiency of LDR has been developed that channels ultrasound towards a favoured direction. This is especially advantageous when using visualization methods like ultrasonic thermography wherein a certain field of view is used and the ultrasonic source is usually placed just outside this region of interest.

Further experimental studies have shown that complete control of the phased matched guided waves is difficult due to the experimental conditions. A total destructive interference was not achieved with the two main reasons being attenuation between the sources and uncertainties in the determination of wavelengths.

As it is, this method is still in a laboratory status with the adjustment of the line source distance according to the excitation frequency and the specimen properties being a mostly manual task. Several solution approaches for automatic adjustment and/or chirp excitation are pending.

### REFERENCES

- [1] SOLODOV, I., J. BAI, S. BEKGULYAN and G. BUSSE. A local defect resonance to enhance acoustic wave-defect interaction in ultrasonic nondestructive evaluation. In: Applied Physics Letters, 2011, 99(21), S. 211911.
- [2] SOLODOV, I., J. BAI and G. BUSSE. Resonant ultrasound spectroscopy of defects. Case study of flat-bottomed holes. In: Journal of Applied Physics, 2013, 113(22), S. 223512. Doi:10.1063/1.4810926

- [3] SOLODOV, I., M. RAHAMMER and N. GULNIZKIJ. Highly-Sensitive and Frequency-Selective Imaging of Defects via Local Defect Resonance. In: The e-Journal of Nondestructive Testing, 2014, 19(12). [http://www.ndt.net/events/ECNDT2014/app/content/Paper/138\\_Solodov.pdf](http://www.ndt.net/events/ECNDT2014/app/content/Paper/138_Solodov.pdf)
- [4] KLEPKA, A., L. PIECZONKA, W.J. STASZEWSKI and F. AYMERICH. Impact damage detection in laminated composites by non-linear vibro-acoustic wave modulations. Damage Mechanics. In: Composites Part B: Engineering, 2014, 65, S. 99-108. Doi:10.1016/j.compositesb.2013.11.003
- [5] DELRUE, S., M. TABATABAEIPOUR, J. HETTLER and K. VAN DEN ABEELE. Non-Destructive Evaluation of Kissing Bonds using Local Defect Resonance (LDR) Spectroscopy: A Simulation Study. Proceedings of the 2015 ICU International Congress on Ultrasonics, Metz, France. In: Physics Procedia, 2015, 70, S. 648-651. Doi:10.1016/j.phpro.2015.08.067
- [6] HAN, X., L.D. FAVRO and R.L. THOMAS. Sonic IR imaging and vibration pattern studies of cracks in an engine disk. In: AIP Conference Proceedings: IOP INSTITUTE OF PHYSICS PUBLISHING LTD, 2003, S. S. 513-516.
- [7] SALERNO, A., A. DILLENZ, D. WU, J. RANTALA and G. BUSSE. Progress in ultrasound lockin thermography. In: Quantitative infrared thermography, QIRT, 1998, 98, S. 154-160.
- [8] MAYTON, D. and F. SPENCER. A design-of-experiments approach to characterizing the effects of sonic IR variables. In: D. BURLEIGH, K. CRAMER und G. PEACOCK, Hg. Proc. Thermosense XXVI: International Society for Optics and Photonics, 2004, S. S. 322-331.
- [9] DAVIS, W. and M. RANKIN. Laser vibrometry and strain gage measurements of thermosonic activation. In: AIP Conference Proceedings: IOP INSTITUTE OF PHYSICS PUBLISHING LTD, 2003.
- [10] BARBER, JR. Some thermoelastic contact problems involving frictional heating. In: The Quarterly Journal of Mechanics and Applied Mathematics, 1976, 29(1), S. 1-13.
- [11] AUDENINO, A.L., V. CRUPI and E.M. ZANETTI. Correlation between thermography and internal damping in metals. In: International journal of fatigue, 2003, 25(4), S. 343-351.
- [12] SOLODOV, I., D. DERUSOVA and M. RAHAMMER. Thermosonic Chladni figures for defect-selective imaging. In: Ultrasonics, 2015, 60, S. 1-5.
- [13] SOLODOV, I., M. RAHAMMER, D. DERUSOVA and G. BUSSE. Highly-efficient and noncontact vibro-thermography via local defect resonance. In: Quantitative InfraRed Thermography Journal, 2015, 12(1), S. 98-111.