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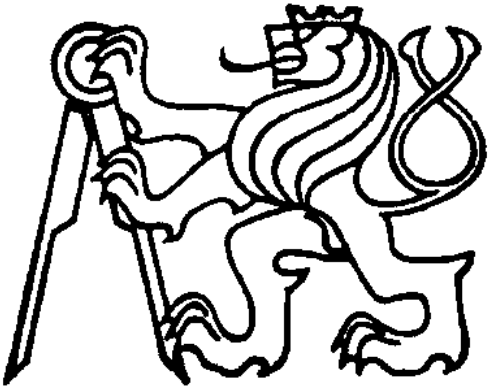

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Measurement

Michal Kubínyi

SIGNAL PROCESSING FOR NDE IN AEROSPACE

Ph.D. Programme: Electrical Engineering and Information Technology

Branch of study Air Traffic Control

Doctoral thesis statement for obtaining the academic title of "Doctor", abbreviated to "Ph.D."

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Opponents:

The doctoral thesis statement was distributed on ……**:**

The defence of the doctoral thesis will be held on ….. **at** ……**. before the Board for the Defence of the Doctoral Thesis in the branch of study Air Traffic Control in the meeting room No. …….. of the Faculty of Electrical Engineering of the CTU in Prague.**

Those interested may get acquainted with the doctoral thesis concerned at the Dean Office of the Faculty of Electrical Engineering of the CTU in Prague, at the Department for Science and Research, Technická 2, Praha.

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1. CURRENT SITUATION OF THE STUDIED PROBLEM

Systems used in aerospace industry are a part of physical principle invaluable tools to maintain safety of air traffic. Each inspection method which uses digital instrumentation poses an option of enhancing acquired information by means of signal processing.

Different demands are directed on a desirable NDE method and optimum signal denoising algorithm. A desired NDE system should be able to conduct the measurement without a direct contact with studied material. Additionally the method should be able to detect and analyse flaws on the surface or in the volume of the material. All these requirements have an only goal and it is to allow fast and effective evaluation of stressed aerospace material. All the measured signals consist of added noise component to signal of interest. Advanced signal denoising algorithms can be applied in order to suppress the noise component.

The disadvantage of available advanced signal denoising algorithms is that they are not optimised for recent NDE methods. New systems allow more sophisticated testing procedures but are also more sensitive to noise. I focus the research to improve the accuracy of current denoising methods and/or to design new, more complex denoising procedures. The main goal is to find significant parameters which describes signal of interest and in an adaptive way adjust signal denoising to achieve a better performance in comparison to already developed signal denoising procedures.

2. AIMS OF THE DOCTORAL THESIS

The main aim of this thesis is to design an adaptive signal denoising algorithm which achieves better signal denoising performance than existing filters. A part of this task is to

analyse and to find significant parameters that describe the signal of interest.

Every inspection method that uses digital instrumentation offers the benefit of accessing a range of information concerning the material or structure that is under evaluation. Chapter 2 of the doctoral thesis deals with genuine signal denoising algorithms that have not been optimised for recent NDT methods, specially for NDT methods such as EMAT. Thus, the thesis aims to design and implement new denoising methods by analysing measured signals and the measurement technology. To achieve the aim of this doctoral thesis the following specific guidelines have to be followed:

I. Apply new ultrasonic transducers in non-destructive testing of aerospace structures.
II. Analyse and estimate the parameters of signals acquired by the transducers.
III. Develop (or use already developed) algorithms for measuring the amount of the signal of interest in the whole signal and discuss the results of a performance comparison over a set of different measured signals and set of signal denoising methods.
IV. Increase the performance of current signal denoising methods by applying the knowledge gained from the previous steps and develop a new signal denoising method for increasing the denoising performance of these methods.
V. Verify the proposed signal denoising methods with promising transducers.

3. WORKING METHODS

A nondestructive evaluation method which is capable of detection flaws inside material without necessity of surface preparation finds application in diverse areas of industry as was presented by Hernandez-Valle and Dixon [2010]. Electro-

Magnetic Acoustic Transducer (EMAT) is a non-contact method to generate ultrasonic waves in conductive materials. In comparison with traditional piezoelectric transducers, EMATs overcome many common problems due to an electromagnetic coupling instead of an acoustic coupling between tested object and transducer.

Ultrasonic inspection with EMAT involves problem with an additive noise which is acquired during a measurement process. The noise can hamper the evaluation of a flaw and other material discontinuities as was discussed by Schuster et al. [1993]. Several signal processing techniques have been developed over the years to reduce noise in ultrasonic signal received by piezoelectric transducers. Typically used linear filtering methods are spatial averaging by Kim et al. [2001], Mattila et al. [1996], digital bandpass filtering by Shankar et al. [1993] and adaptive filtering by Bamber and Daft [1986] Deaton and Wagner [1994], Liu et al. [1997]. Especially adaptive signal processing algorithms are under an intensive research due to theirs ability to handle spatially varying noise. Non-linear techniques, which are often frequency domain based, like Split Spectrum Processing by Karpur and Canelones [1992], Neural Networks by Vicen et al. [2004] and Wavelet de-noising by Hayward and Lewis [1989] Lazaro [2002] Pardo et al. [2006] were used. Kalman filtering was applied by Kuc [1979] for model based time corrections in time-of-flight diffraction. To correct errors in case of non-linear system model, extended Kalman filtering was evaluated by Sekmen and Barshan [2001]. The band-pass filtering assumes that random process representing the received signal consists of uncorrelated random processes corresponding to the noise and signal where theirs frequency spectra densities don't overlap. If theirs spectral densities overlap, linear filtering methods (common and adaptive) are not suitable which was proved by Vicen et al. [2004]. Non-linear filtering is an alternative method which was already verified on piezoelectric transducers by Matz et al. [2009].

4. RESULTS

This thesis presents a novel extension of widely-used signal wavelet denoising method based on fusion of information, see Figure 1.

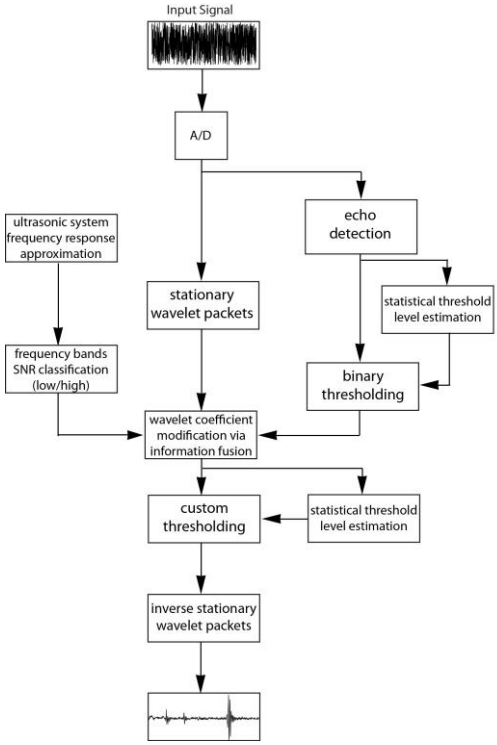

Figure 1 Novel signal denoising algorithm

Three sources are used for information fusion:

- ultrasonic system frequency response approximation
- wavelet packet decomposition
- time-domain echo detection

Multiple signal processing domains explore various characteristics of the noise and the signal of interest. Information fusion based on these domains improves the signal filtering performance over single method processing.

The frequency band of the ultrasonic transducer is limited and the frequency Power Spectral Density (PSD) is estimated from a measured signal. The PSD is used to differentiate frequency ranges with and without the ultrasonic signal carrier frequency. We assume that this estimation corresponds to the frequency response estimation of the ultrasonic transducer.

Stationary Wavelet Packets (SWP) decomposition of the EMAT signal represents an estimation of the EMAT signal separated into frequency bands. SWPs which correspond to high-PSD will include mainly the signal of interest. On the other hand, SWPs corresponding to low-PSD will include mainly the noise component of the measured signal. The SWP threshold level is adjusted according to its frequency position in PSD estimation. This idea introduces an apriori information based filtering concept to WT. The EMAT system frequency response is considered time-invariant, and a fixed frequency characteristic is therefore used.

The EMAT ultrasonic signal includes at least one ultrasonic echo reflected from the tested material backwall. This corresponds to a pulse-echo technique for a single probe setup. The backwall echo is utilised as a correlation pattern for extracting the flaw echo from noise (using pulse detection theory). The result of ultrasonic echo detection in the time domain is used for ultrasonic echo enhancement in the time-frequency domain represented by the Stationary Wavelet Packet (SWP) coefficients.

The proposed idea of merging information from time-domain echo detection and wavelet decomposition forms the second information source.

The filtering algorithm merges coefficients from WT, the ultrasonic echo detector, and the frequency-domain analysis.

The algorithm consists of five steps:

1) low/high PSD frequency band detection

2) ultrasonic echo detection

3) signal transformation via wavelets

4) wavelet coefficient thresholding

5) signal reconstruction from the filtered coefficients

Threshold level estimation is a part of echo detection and wavelet processing. The goal is to use a statistical model for wavelet coefficients and an echo detector to estimate the signal amplitude which represents the margin between the noise and the signal of interest. If the standard deviation is an estimation of the noise level, then this value multiplied by three covers 99% of the possible amplitudes of the noise component. This statistical model is used for both echo detection and WP thresholding. The distribution of the noise was measured similar to a normal distribution. The Gaussian curve does not fit the amplitude distribution of an input signal, and it is necessary to introduce a correction factor to apply a standard deviation threshold. Echo detection and wavelet thresholding use the same threshold level estimator.

The result of a new signal denoising algorithm is presented in Figure 2. The benchmark is based on Signal to Noise Ratio Enhancement (SNRE). Processed signal was acquired by EMAT probe and it exhibits low signal to noise ratio.

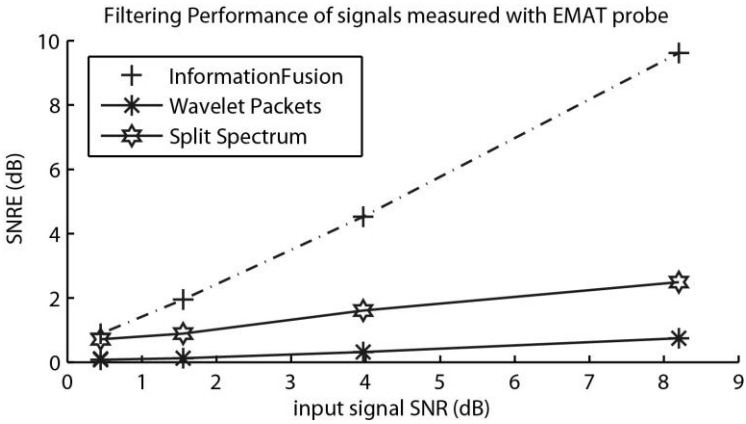

Figure 2 Performance comparison of signal denoising methods with low signal to noise ratio input signal

5. CONCLUSION

Submitted thesis presents a novel signal denoising method for ultrasonic EMAT signals based on fusion of information from multiple domains (time, frequency and the time-frequency domain). The information from a statistical echo detector, the apriori known frequency characteristics of an EMAT signal and the standard deviation of the wavelet packet coefficients influence the threshold in the stationary wavelet packet denoising procedure. The use of information from multiple sources causes better performance of the filtering in terms of Signal-to-Noise Ratio Enhancement (SNRE) over standard single source methods.

The performance of the proposed signal filtering method was evaluated on artificial and real signals by means of SNRE under various SNR conditions. The experiments proved that the proposed method increases SNR two times for an EMAT signal in comparison with SSP or standard wavelet based filtering algorithms.

6. THESIS CONTRIBUTION

I will summarise the contribution made by my doctoral work by listing four of my publications in WoS Journals, with notes.

Duffard, R. - Kumar, K. - Pirrota, S. - Salatti, M. - Kubíınyi, M. - et al.: A multiple rendezvous, sample-return mission to 2 near-Earth asteroids *In: Advances in Space Research, 2011. ISSN 0273-1177.*
I carried out research within an international team on aerospace projects, materials and, especially, on tools that were needed for the project.

A. - Ramos, H.G. - Ribeiro, A.L., Kubíınyi, M.: Measuring Interface for an ECT System *In: Przeglad Elektrotechniczny. 2011, vol.87, no. 1, 266-271. ISSN 0033-2097*
I continued with research on the design and implementation of an NDT system. I designed some eddy current probes and tested them on aerospace structures.

Kubíınyi, M. - Dočekal, A. - Ramos, H.G. - Ribeiro, A.L.: Signal Processing for Non-contact NDE *In: Przeglad Elektrotechniczny. 2010, vol. 86, no. 1, p. 249-254. ISSN 0033-2097.*
I applied some recently published signal processing methods in order to make a comparison of different NDT methods. I used a laboratory-produced eddy current system and an experimental EMAT system.

Kubíınyi, M. - Kreibich, O. - Neužil, J. - Šmíd, R.: Novel S-Transform Information Fusion for Filtering Ultrasonic Pulse-Echo Signals *In: Przeglad Elektrotechniczny. 2011, vol. 87, no. 1, p. 290-295. ISSN 0033-2097.*
I used some of the latest available methods for a study of the signal parameters of EMAT instrumentation. I used the results for preliminary work on the design of a new signal denoising algorithm.

Kubínyi, M. - Kreibich, O. - Neužil, J. - Šmíd, R.: EMAT Noise Suppression using Information Fusion in Stationary Wavelet Packets *In: IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 2011. ISSN 0885-3010.*

The final stage of the research done for this dissertation was the design and verification of a new signal denoising algorithm that uses information from different domains. It is able to combine the information with an synergetic effect, and it this way it improves the ultrasonic signal more than if the domains were used separately.

The experiments presented in the thesis has shown that the new signal denoising algorithm produces signals with less noise than other methods discussed here. These results are achieved by adjusting general denoising algorithms and fusing the benefits from each method.

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List of candidate's works relating to the doctoral thesis

"Crack" project at the Instrumentation Laboratory of Instituto de Telecomunicações at Lisbon, Portugal under supervision of prof. Helena Geirinhas Ramos and prof. Artur Lopes Ribeiro, 2008.

Papers in WoS Journals

Kubínyi, M. - Kreibich, O. - Neužil, J. - Šmíd, R.: EMAT Noise Suppression using Information Fusion in Stationary Wavelet Packets *In: IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control. ISSN 0885-3010.* **(55%)**

Kubínyi, M. - Kreibich, O. - Neužil, J. - Šmíd, R.: Novel S-Transform Information Fusion for Filtering of Ultrasonic Pulse-Echo Signals *In: Przeglad Elektrotechniczny. 2011, vol. 87, no. 1, p. 290-295. ISSN 0033-2097* . **(55%)**

Ramos, H.G. – Ribeiro, A.L. – Kubínyi, M.: Measuring Interface for an ECT System *In: Przeglad Elektrotechniczny. 2011, vol. 87, no. 6, p. 266-271. ISSN 0033-2097.* **(33%)**

Kubínyi, M. - Dočekal, A. - Ramos, H.G. - Ribeiro, A.L.: Signal Processing for Noncontact NDE *In: Przeglad Elektrotechniczny. 2010, vol. 86, no. 1, p. 249-254. ISSN 0033-2097.* **(85%)**

Duffard, R. - Kumar, K. - Pirrota, S. - Salatti, M. - Kubíınyi, M. - et al.: A multiple rendezvous, sample-return mission to 2 near-Earth asteroids *In: Advances in Space Research, 2011. ISSN 0273-1177.* **(7%)**

Papers in WoS Journals under review

Kubínyi, M. - Kreibich, O.: Performance Evaluation of an Advanced Ultrasonic Testing System on Aircraft Material *In: IEEE Aerospace and Electronic Systems. ISSN 0885-8985.***(75%)**

Papers in Other Journals

Kubínyi, M.: Descriptions Methods for 3D Visualization of Eddy Current Signatures *In: e-Journal of NDT. 2010, vol. 2005, no. 5. ISSN 1435-4934.***(100%)**

Other Papers

Kubínyi, M - Šmíd, R.: Comparison of Cascade and Concurrent Signal Denoising Methods *In: IEEE International Ultrasonics Symposium 2011 . Orlando: IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society , 2011.* **(95%)**

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Kubínyi, M.: Descriptions Methods for 3D Visualization of Eddy Current Signatures *In: Defektoskopie 2009. Praha: Česká společnost pro nedestruktivní testování, 2009, p. 81-85. ISBN 978-80-214-3973-3.* **(100%)**

Kubínyi, M. - Dočekal, A. - Ramos, H.G. - Ribeiro, A.L.: Non-Contact NDE for Thin Aerospace Structures *In: The 13th Asia-Pacific Conference on Non-Destructive Testing. Yokohama:Japanese Society for Non-Destructive Inspection, 2009, p. 117-118.***(85%)**

Kubínyi, M. - Šmíd, R.: Novel Eddy Current and EMAT Probes Performance Comparison *In: 8. mezinárodní vědecká konference Měření, diagnostika a spolehlivost palubních soustav letadel. Brno: Univerzita obrany, Fakulta vojenských technologií, 2008, p. 33-38. ISBN 978-80-7231-555-0.* **(95%)**

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Kubínyi, M. - Šmíd, R. - Ribeiro, A.L.: EMAT – Eddy Currents and Ultrasound *In:PEGASUS-AIAA Student Conference. Prague: Czech Technical University, 2008.* **(34%)**

Ramos, H.G. - Ribeiro, A.L. - Radil, T. - Kubínyi, M. - Paval, M.: Signal Processing in an Eddy Current Non-Destructive Testing System *In: 16th IMEKO TC4 International Symposium and 14th*

International Workshop - Proceedings. Florence: University of Florence, 2008, p. 223-228. ISBN 978-88-903149-3-3. **(20%)**

Kubínyi, M. - Šmíd, R.: Sensitivity Increasing of an Ultrasonic EMAT Materiology *In: The third AIAA-Pegasus Student Conference. Napoli: Universita degli Studi di Napoli "Federico II",2007.* **(95%)**

Kubínyi, M. - Šmíd, R.: Testing of an Airplane Structures with Non-contact Ultrasound Defectoscopy *In: MOSATT 2007, Proceedings of the International Scientific Conference "Modern Safety Technologies in Transportation". Košice: Slovak Transport Society at the Slovak Academy of Sciences, 2007, p. 160-164. ISBN 978-80-969760-2-7.* **(95%)**

Kubínyi, M. - Šmíd, R.: Noise and Signal Processing for EMAT NDT *In: MDS - Měření, diagnostika, spolehlivost palubních soustav letadel - 7. mezinárodní vědecká konference. Brno: Univerzita obrany, Fakulta vojenských technologií, 2007, p. 81-87. ISBN 978-80-7231-281-8.* **(95%)**

International recognition

I was a chairman of the ultrasonic NDT session on the 13th Asia-Pacific Conference on Non-Destructive Testing, Yokohama 2009. Conference organized by Japanese Society for Non-Destructive Inspection. I had invited lecture on image processing for Digital Radiography in Industry on International NDE for Safety Conference 2011 held in Ostrava, Czech Republic.

SUMMARY

The scope of the proposed thesis is research of signal processing methods used for non-destructive testing in aerospace. The research work begun with an extensive study over non-destructive methods used in aerospace. Based on this research work an ultrasonic testing was chosen to be testing ground for the further research. After year 2001 NASA published proposal on a project focused on evaluation of EMAT used for non-destructive in space. STARMANS LTD.

developed experimental probes suitable for this application. These probes were used for this research. Submitted thesis made an overview over physics governing EMAT. Acquired ultrasonic signals were analysed. A further research was made to analyse sources of noise in the measurement chain. Received ultrasonic data was analysed in time and frequency domain. Presented result is a deep understanding of the received data. Recent advances is signal denoising were studied in order to develop more efficient signal denoising methods for NDT instrumentation used in aerospace. A new signal denoising method was based on the study of ultrasonic signals and recently developed signal denoising methods. The key advantage of the developed method is in positive combination of information gained from apriori known signal characteristics. The new method implements information fusion based on different transformations of a signal. This approach produces a better denoising performance than previously published methods. Proposed method can be used in other instrumentation used in aerospace like radar, where signals embody similar characteristics like discussed ultrasonic signal. Presented research work offers original contribution to application of EMAT probes to NDT in aerospace and novel denoising method for ultrasonic signals.

SHRNUTÍ

Předmětem této práce byl výzkum v oblasti zpracování signálu pro nedestruktivní testování leteckých materiálů. V rámci jejího řešení byla provedena studie nad nedestruktivními metodami používanými v letectví. Na základě této studie byla vybrána oblast ultrazvukového zkoušení materiálů. Po roce 2001 byla zveřejněna dokumentace Národního úřadu pro letectví a vesmír Spojených států amerických, kde byla zveřejněna výzva pro vývoj měničů EMAT pro nedestruktivní zkoušení ve vesmíru. Firma STARMANS vyvinula a vyrobila experimentální sondy EMAT, které byly použity v této práci. V rámci předkládané práce byly zdokumentovány fyzikální principy, na základě kterých tyto sondy pracují. Následně byly analyzovány ultrazvukové signály, které sondy generují. Byla též zkoumána citlivost sond na příjem ultrazvukových signálů. Byl analyzován měřicí řetězec ultrazvukových signálů a i vliv vnějšího prostředí. Získaná digitální data byla podrobena analýze jak v časové tak frekvenční rovině. Výsledkem této analýzy byla dobrá znalost

charakteristik zkoumaných signálů. Za účelem potlačení šumů a lepšího využití sond EMAT v leteckém průmyslu byly zkoumány současné metody zpracování signálů. Na základě dobré znalosti charakteristiky zkoumaných signálů a současných metod potlačení šumu i v jiných oblastech než nedestruktivní testování byla navržena nová metoda potlačení šumu. Jádro přínosu této metody spočívá v pozitivním spojení informace z odlišných přístupů náhledu na zpracovávaný signál a jeho užitečnou složku. Nově navrhnutá metoda potlačení šumu v ultrazvukovém signálu využívá charakteristiky zkoumaného signálu tak aby dosáhla vyššího potlačení šumu než do současné doby jiné prezentované metody. Na základě využití podobnosti s jiným aplikacemi v letectví lze použít předkládanou metodu například i v radarové technice. Předkládaná práce představuje původní výzkum v oblasti využití sond EMAT v leteckém nedestruktivním zkoušení a následný vývoj nové metody potlačení šumu v ultrazvukovém signálu.

RÉSUMÉ

Michal Kubínyi was born in 1982 in Prague. He enrolled to Czech Technical University in Prague in 2001 to study a program Electrical Engineering and Informatics on Faculty of Electrical Engineering. He pursued his degree during bachelor branch Cybernetics and Measurement, and master branch Aircraft Control and Information Systems. He graduated in 2007 and continued in his scientific endeavor under supervision of Assoc. Prof. Radislav Šmíd in signal processing.

Mr. Kubínyi studied ADC & DAC Metrology on University of Sannio, Benevento, Italy in 2007. In 2008 he joined research group of prof. H.G. Ramos and prof. A.L. Ribeiro at the Instituto Superior Técnico, Lisboa, Portugal. Later in 2008 he has participated on space studies program organized by European Space Agency. In 2009 he has visited Tokyo Institute of Technology where he has studied development of ultrasonic transducers and suitable signal processing methods. Michal Kubínyi is presenting his research in order to obtain doctor degree.