

Investigation of field suitable microwave cavity measurement approaches

Der Fakultät für Ingenieurwissenschaften

der Universität Bayreuth

zur Erlangung der Würde eines

Doktor-Ingenieurs (Dr.-Ing.)

genehmigte Dissertation

von

M. Sc. Eng. Radosław Królak

aus

Morąg, Polen

Erstgutachter: Prof. Dr.-Ing. Gerhard Fischerauer

Zweitgutachter: Prof. Dr.-Ing. Dr.-Ing. habil. Robert Weigel

Tag der mündlichen Prüfung: 31. Januar 2017

Lehrstuhl für Mess- und Regeltechnik

Universität Bayreuth

2017

Bayreuther Beiträge zur Sensorik und Messtechnik

Band 21

Radoslaw Królak

**Investigation of field suitable microwave cavity
measurement approaches**

Shaker Verlag
Aachen 2017

Bibliografische Information der Deutschen Nationalbibliothek

Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über <http://dnb.d-nb.de> abrufbar.

Zugl.: Bayreuth, Univ., Diss., 2017

Copyright Shaker Verlag 2017

Alle Rechte, auch das des auszugsweisen Nachdruckes, der auszugsweisen oder vollständigen Wiedergabe, der Speicherung in Datenverarbeitungsanlagen und der Übersetzung, vorbehalten.

Printed in Germany.

ISBN 978-3-8440-5331-9

ISSN 1862-9466

Shaker Verlag GmbH • Postfach 101818 • 52018 Aachen

Telefon: 02407 / 95 96 - 0 • Telefax: 02407 / 95 96 - 9

Internet: www.shaker.de • E-Mail: info@shaker.de

Editorial

The optimum operation of a combustion process requires that one know the inner state of the exhaust catalyst nowadays indispensable for exhaust-gas aftertreatment. To date, one does not measure this state (e. g., the oxygen storage ratio in a three-way catalyst, or TWC) directly, but rather infers it from measurements upstream and downstream of the catalyst (in the case of the TWC, this is what lambda probes are used for). A direct method based on the interaction between microwaves and the catalyst has been described quite thoroughly in the literature by now, but these results are based on equipment such as vector network analyzers (VNA) which cannot be used as field devices for cost and size reasons.

The present work investigates hardware and software approaches which have the potential to be used in field devices deployable in vehicles and similar environments on a routine basis for in-situ non-destructive catalyst-state diagnostics. It is demonstrated that scalar reflectometry lends itself to the task of monitoring a housed catalyst if an appropriate signal processing strategy is implemented.

In the course of the work, two demonstrators have been designed, implemented and characterized, and the methodology of extracting resonance frequencies from (even shallow) return-loss spectra has been investigated. It is shown that the precision of the return loss measured by the demonstrators is acceptable by comparison to commercial VNAs and that the accuracy is about 0.03 dB. Based on this, resonance frequencies in the range from 1 to 6 GHz can be determined at an effective rate of 10 to 40 Hz, which is an order of magnitude faster than previously possible with VNA-based systems.

The measurement system is validated through dynamic tests with a TWC subjected to gas flows of varying oxygen content. The resulting agreement between the TWC loading state and the measured resonance frequency is convincing. This, together with further results on the short- and long-time stability of the demonstrators and with cost estimates, corroborates the applicability of the approach to the task of monitoring an electrochemical system in situ by a field device.

Bayreuth, May 2017

Prof. Dr.-Ing. Gerhard Fischerauer, Prof. Dr.-Ing. Ralf Moos

*To my dear and loving wife Sunny,
Who convinced me to pursue a Ph.D. degree.*

Index

	Page
Index	v
List of abbreviations	viii
List of symbols	ix
1 Introduction	1
1.1 State of the art	1
1.2 The objective of this work	5
2 The basics	7
2.1 Scattering parameters	7
2.2 Reflectometry	9
2.3 VNA measurements	10
2.4 Resonant cavities	11
2.5 Quality factor	13
2.6 Normal distribution	14
3 Swept reflectometer concept for resonance measurements	15
3.1 Phase approach results	17
3.2 Magnitude approach results	18
3.3 Other concepts	19
4 Hardware realization	20
4.1 Hardware setup – demonstrator A	20
4.2 Control algorithm	21

4.3 Performance of demonstrator A	23
4.4 Validation	31
4.5 Performance increases – demonstrator B	34
4.6 Performance gains over demonstrator A	36
5 Further characterization	42
5.1 Signal quality	42
5.2 Signal drift	45
5.3 Output power stability	46
5.4 Uncertainty of amplitude measurement	47
5.5 Demonstrator B compared to other systems	49
5.6 Summary	51
6 Q estimation using measurement uncertainty	53
6.1 Modelling of a noisy S_{11} curve	54
6.2 Estimation of resonance frequency.	56
6.3 Properties of the CDF resonance estimation model	59
6.4 Monte–Carlo validation	64
6.5 Experimental validation	67
6.6 Q factor estimation and other methods' properties	70
6.7 Accuracy	75
6.8 Outlook	76
7 Using the CDF model for other phenomena	77
7.1 A transmission–type cavity	77
7.2 Morse potential	78
7.3 Planck's law	80

8 Summary	82
9 Zusammenfassung	83
Appendix	85
A A more detailed hardware description	85
Literature	91