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POLITECHNIKA ŚLĄSKA
Biuro Rady Dyscypliny
Automatyka, Elektronika, Elektrotechnika
i Technologie Kosmiczne

Częstochowa, 09.09.2026 r.

wpłynęło dnia 11.09.2026

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Review of the doctoral thesis by Faisal Saleem, MSc (Eng)
„Measurement uncertainty of quantity modelled with non-integer
order differ-integral equations”

The doctoral thesis is supervised by Józef Wiora, Ph.D., D.Sc., Prof. at the Silesian University of Technology, with Alicja Wiora, Ph.D. serving as co-supervisor. The doctoral programme is conducted within the discipline of “Automation, Electronics, Electrical Engineering and Space Technologies” at the Faculty of Automation, Electronics and Computer Science of the Silesian University of Technology. This review was commissioned by the Chair of the Disciplinary Board for “Automation, Electronics, Electrical Engineering and Space Technologies”, Prof. Ph.D., D.Sc. Adam Gałuszka, by letter dated 31 July 2026, (RDAE-ETK.512.16.2026) on the basis of resolution No. 56/2026 of the Disciplinary Council for “Automation, Electronics, Electrical Engineering and Space Technologies” dated 16 June 2026 (RDAE-ETK.0211.56.2026).

This thesis is peer-reviewed in accordance with the provisions of art. 186 and 187 of the Act of 20 July 2018, *Law on Higher Education and Science* (Journal of Laws of 2022, item 574, as amended, and Journal of Laws of 2023, item 742, as amended).

This review has also been carried out in accordance with the recommendations of the Chair of the Disciplinary Board, Prof. Adam Gałuszka, as set out in the aforementioned letter dated 31 July 2026, (RDAEETK.512.16.2026) and taking into account the best practices described by the Council for Scientific Excellence (CSE) in the guides available on the CSE’s website – accessed on 5 July 2023. This assessment also took into account the latest recommendations of the Vice-Chair of the Council for Scientific Excellence, Prof. Grzegorz Węgrzyn, who, with regard to the assessment of doctoral theses, recommends that: “In doctoral proceedings, doctoral awarding bodies should apply the same principles of substantive assessment of applications as those applied by the CSE when considering applications for the title of professor”, which boils down to the fact that “the CSE does not expect reviewers to carry out a bibliometric analysis of candidates’ academic work or to assign a numerical score to their body of work. Such an analysis requires no expertise or knowledge of the relevant academic discipline and could be carried out by any administrative staff member in the CSE Office”. It further recommends that: “The internal regulations of doctoral-awarding bodies should not contain quantitative limits, in particular those specifying minimum thresholds for bibliometric indicators or point scores.” This means that: “The CSE expects reviewers to carry out a substantive analysis of candidates’ academic achievements. To familiarise oneself with their publications and determine whether the results of their academic work have made a significant contribution to science”.

The title of the doctoral thesis on which the application for the award of a doctoral degree is based

The title and subject matter of the doctoral thesis concern the analysis of uncertainty in quantities described by dynamic fractional-order equations. This subject matter integrates metrology, model identification, fractional calculus and control theory, whilst falling within the scope of the discipline “Automation, Electronics, Electrical Engineering and Space Technologies”. In this regard, the PhD candidate has developed an original approach to the assessment of uncertainty in systems exhibiting fractional-order properties, focusing on the assessment of uncertainty propagated by fractional-order model parameters determined during the

identification process. The PhD candidate has developed a direct approach to uncertainty propagation based on time-dependent sensitivity coefficients, derived analytically from fractional-order differential-integral equations. The proposed method takes into account the covariance matrix of the estimated parameters and utilises the law of uncertainty propagation to quantify the uncertainty associated with these parameters.

An assessment of the structure of the doctoral thesis, including information on its individual components

The thesis under review, in its original English version, comprises 185 pages of main text and includes an abstract, a list of the PhD candidate's publications, and lists of: contents, figures, tables, pseudocodes for the author's original algorithms, acronyms, and a list of symbols used. The thesis contains 67 figures and 28 tables and is divided into 9 main chapters, totalling 221 pages.

It should be emphasised that the subject matter of this doctoral thesis relates to many years of research and represents a significant development of the achievements of its supervisor, Professor Józef Wiora.

The thesis consists of the following sections:

Chapter 1: “*Introduction*”, which provides a brief overview of the main content of the thesis, discusses the problem to be addressed in the following sections, and explains its significance for science and why the PhD candidate undertook to address it.

Chapter 2: “*Background and Literature Review*”, which presents the theoretical foundations and key definitions related to metrology and fractional-order (FO) calculus. This chapter also includes definitions of common approximation methods used for the practical implementation of FO operators. Furthermore, selected works from the literature relevant to the objectives of this thesis are discussed.

This is a very comprehensive literature review. It is a pity that the PhD candidate did not refer here to the works of Professors Adam Żuchowski and Stanisław Skoczowski from the West Pomeranian University of Technology in Szczecin. In this regard, amongst other things, Professor Żuchowski has written numerous papers on dynamic systems with a fractional order of dynamics (inertia), the so-called Strejc models, whilst also being the founder of the field of “*dynamic metrology*” within metrology. A list of some of these works can, for example, be found at: https://yadda.icm.edu.pl/baztech/search/page.action?qt=SEARCH&q=sc.general*c_0keywords_0eqs.model%2BStrejca*1_0. The Strejc model has only three parameters: the static gain coefficient K , the time constant T , and the order of dynamics α , e.g. fractional – see equation (3.3) in the PhD candidate's thesis. These works present, amongst other things, the concept of creating a Strejca model with a fractional order of inertia expressed using piecewise functions. The Strejca model is also suitable for describing and identifying the dynamics of objects with step-function characteristics that increase monotonically.

It is good that, at least in this respect, the PhD candidate included some of my publications on Strejc's models – that is, dynamic systems with fractional-order dynamics – in the bibliography. It is worth noting here that the Strejc model concerns linear dynamical systems, whilst the PhD candidate, in his doctoral thesis, also considered non-linear dynamical models, and furthermore under conditions where disturbances are present.

Chapter 3: “*Case Studies and Experimental Data*”, presents the case studies used to validate the proposed methods. Three systems were considered: two simulation models in the MATLAB/Simulink environment and one laboratory test workstation. The first system is a first-order, delay-free Single-Input Single-Output (SISO) inertial model. The transfer function (TF) of this system is used to evaluate steady-state errors and dynamic inaccuracies resulting from the IO approximation. The second system is TRAS, which operates as a Multi-Input Multi-Output (MIMO) system. Its non-linear model in the Simulink environment is used to evaluate the design quality of Fractional-Order (FO) controllers and the impact of IO

approximation methods. The third system under consideration is a non-linear, SISO-type laboratory flow rate measurement system.

Chapter 4: “*Accuracy of Approximation Methods*” describes an analysis of the accuracy of integer-order (IO) approximation methods used to implement FO models and controllers. This chapter expands on the results published in one of the PhD candidate’s earlier papers.

Chapter 5: “*Integer-Order Modelling*” presents the modelling approach applied to the flow system analysed in the thesis. As the system exhibits different dynamics for different excitation frequencies, separate third-order transfer functions were determined from the experimental input-output data (IOD). In addition, second-order models were estimated to enable their comparison. A FO modelling approach is presented for a laboratory flow rate measurement system characterised by non-linear dynamics, measurement uncertainty and variable sampling intervals. This is a very comprehensive chapter of the thesis.

Chapter 6: “*Fractional-Order Modeling*” presents a framework for FO modelling of a laboratory flow rate measurement system with a constant input signal, characterised by non-linear dynamics, measurement uncertainty and variable sampling intervals. The proposed proprietary algorithm takes into account the non-linear nature of the system and the associated uncertainty component through the construction of a nominal FO model. The model identification task was formulated as an optimisation problem, in which the model parameters were determined directly on the basis of experimental data.

Chapter 7: “*FO controller design*” – simple tuning rules for the FO-PI controller parameters are proposed here, based on frequency-domain methods. This approach avoids excessive complexity whilst retaining the advantages of fractional-order dynamics. A structured procedure for selecting controller parameters is presented. The design takes into account the requirements for the cut-off frequency of the gain, the phase margin and the flatness of the phase response, which ensures the robustness of the closed-loop system.

Chapter 8: “*Dynamic uncertainty propagation of FO models*” – a method for constructing time-dependent sensitivity coefficients based on a probabilistic description of the identified parameters of the FO model is proposed here. A direct approach to assessing the measurement uncertainty component propagated through the parameters identified in the dynamic FO model is then presented.

Chapter 9: “*Conclusions and future directions*” summarises the research findings, scientific contributions and methodological limitations presented in the individual chapters of the thesis. The PhD candidate summarised the achievements made during the course of his doctoral research. It also outlines directions for further research aimed at overcoming the identified limitations. It is suggested that future research could consider the adaptive selection of the truncation order as a decision variable in GL (Grünwald-Letnikov) optimisation. This approach may reduce computation time and enable real-time application.

The structure of the thesis is essentially sound; I shall describe minor comments in this regard later in this review. The thesis is written in good scientific and technical language, and the original version is in English. The thesis is very extensive (221 pages); therefore, the material could have been presented in a more condensed manner and the length of the thesis could have been reduced to 120 ÷ 150 pages, which is the typical length for doctoral theses.

Despite these minor comments, it must be said that the PhD candidate has demonstrated an ability to write academic papers.

An assessment of the literature reviewed in the doctoral thesis

The selection of references is appropriate. Nevertheless, the reviewer noted that the PhD candidate did not refer to the works of Professors Adam Żuchowski and Stanisław Skoczowski. I have addressed this point above. This is a pity, as these professors had previously worked on similar topics concerning dynamic fractional equations. However, the innovation contributed to science by the PhD candidate in this area is his original approach to the assessment of uncertainty in systems exhibiting fractional-order properties, focusing on the assessment of

uncertainty propagated by the parameters of fractional-order models determined during the identification process.

Furthermore, in his doctoral thesis, the PhD candidate also considered non-linear dynamic models, particularly under conditions where disturbances are present. This represents an innovative approach to solving this problem.

Statement and assessment of the aim of the PhD candidate's thesis

The aim of the thesis was to investigate whether FO modelling can effectively capture the complex non-linear behaviour of a system.

Measurements in dynamic systems concern both transient and steady-state conditions. Analysing only the steady state may lead to the omission of the amplification effect or mutual interaction occurring in transient states. This is undesirable, as in many systems transient responses dominate the overall behaviour of the system and affect both the accuracy of the modelling and the performance of controllers in closed-loop systems. Existing studies focus mainly on nominal accuracy or controller tuning, offering limited insight into the mechanisms of uncertainty propagation. Furthermore, the impact of IO approximations on uncertainty propagation also requires in-depth analysis. This shortcoming is of significant importance, as each of these factors directly affects the reliability of the modelled system behaviour. In addition, modelling the dynamics of physical systems encounters difficulties arising from non-linearity and the presence of measurement noise.

The PhD candidate has addressed and successfully resolved these issues in his thesis.

Description and evaluation of the research methods employed

This is a highly comprehensive theoretical study, but one supported by experimental research conducted using a test rig constructed by the PhD candidate and illustrated in Figs. 3.3–3.5, concerning the development of a method for assessing the uncertainty propagated by the parameters of FO models.

The mathematical framework and research methods employed are correct.

Assessment of the section of the doctoral thesis concerning the discussion of research results

The doctoral candidate proposed an integrated approach to modelling, control and the assessment of uncertainty propagated by FO model parameters. The thesis contributes to the development of the theoretical foundations and practical applications of FO methods in modelling, control and metrology. In this regard, the PhD candidate's original achievements are:

- the development of a conceptual framework for the assessment of uncertainty propagated by FO model parameters,
- the formulation of practical recommendations for integrating FO modelling with uncertainty analysis,
- the development of tuning rules for FO-PI controllers using frequency-domain methods and their verification for two case studies,
- the formulation of FO modelling as an optimisation problem that takes measurement uncertainty into account, and its experimental validation,
- an analysis of the impact of FO operator implementation on uncertainty propagation.

It is a pity that, in this regard, the PhD candidate did not refer to the work of Professors Adam Żuchowski and Stanisław Skoczowski – I wrote about this earlier.

Information on the practical application of the research findings obtained

Accurate measurement of liquid flow is of crucial importance in many practical applications, ranging from domestic installations to large-scale industrial processes. The correct

operation of water distribution and treatment systems depends on reliable flow control. Similar requirements apply, for example, in heating, condensation and irrigation systems, as well as in liquid dosing and discharge systems. In many applications, it is necessary to maintain a set flow rate in a steady state. An intelligent control system ensures that this task can be carried out. Controller design methods are based on accurate mathematical models, which enable control synthesis that guarantees the desired system behaviour. For this reason, an appropriate dynamic model of the process is key information, essential for the effective design and implementation of control systems.

To this end, a comparison is presented between controllers designed using the proposed approach and classical IO and PID-type FO controllers. The analysis carried out showed that the approximation methods used have a significant impact on the behaviour of the closed-loop system and its robustness. The results presented provide both a theoretical basis and practical guidelines for the design of effective and implementable FO controllers for non-linear dynamic systems.

It is precisely here that the results of this research can be put into practice.

Information on any irregularities found in the doctoral thesis under assessment

Whilst reading the doctoral thesis under assessment, the reviewer did not notice any irregularities.

Assessment of whether the doctoral thesis presents an original solution to a scientific problem

Yes, the doctoral thesis under review presents an original solution to a scientific problem. A description of the original, author-developed solutions to scientific problems and the original, author-developed research methods employed is provided above in the section concerning the: *“Assessment of the section of the doctoral thesis concerning the discussion of research results”*.

An assessment of whether the doctoral thesis demonstrates the doctoral candidate’s general theoretical knowledge in the discipline of “Automation, Electronics, Electrical Engineering and Space Technologies” and their ability to conduct independent research

The doctoral thesis demonstrates the PhD candidate’s general theoretical knowledge in the discipline of *“Automation, Electronics, Electrical Engineering and Space Technologies”* and their ability to conduct independent research. This is further confirmed by the PhD candidate’s excellent publications, co-authored with his supervisor and co-supervisor in prestigious journals such as: *“Measurement”* (200 Ministry of Science and Higher Education points), *“Scientific Reports”* (140 points) and *“Communications in Nonlinear Science and Numerical Simulation”* (100 points) in journals assigned to this discipline. Furthermore, the PhD candidate has published high-quality papers in the proceedings of recognised international conferences: *“Conference on Automation 2024 and 2026”*, *“Signal Processing: Algorithms, Architectures, Arrangements, and Applications 2025”* and *“IMEKO, TC-6 International Conference on Metrology and Digital Transformation 2025”*.

Final conclusion

The doctoral thesis submitted for review by Faisal Saleem, MSc (Eng), which forms the basis of his application for the degree of Doctor of Technical Sciences, is written in accordance with the rules. The structure of the thesis and the order in which individual publications are cited are correct. The doctoral candidate rightly highlights his own achievements. ***On the basis of a thorough analysis of the thesis, I can state that no fundamental critical comments of a***

substantive nature arise.

The minor comments set out above are intended to inspire and encourage the doctoral candidate to continue his work in this field. The reviewed doctoral thesis by Faisal Saleem, MSc (Eng), entitled “*Measurement uncertainty of quantity modelled with non-integer order differential integral equations*”, constitutes a sound, independent contribution by the doctoral candidate to the technical sciences, particularly in the field of the theoretical foundations and practical applications of FO methods in modelling, control and metrology. The results obtained are of significant cognitive importance and may be utilised in further research in this field.

On this basis, it must be concluded that the PhD candidate possesses general theoretical knowledge in the scientific discipline of “Automation, Electronics, Electrical Engineering and Space Technologies”, has undertaken to solve an original problem and has resolved it using sound research methods, and has demonstrated the ability to conduct independent scientific research. I therefore conclude that the doctoral thesis submitted to me for assessment, which forms the basis of the application for the award of the degree of Ph.D. in Engineering to Faisal Saleem, MSc (Eng), requires no additions or corrections and meets the conditions and requirements set out for Ph.D., as set out in Article 187(1) and (2) of the *Act of 20 July 2018 on Higher Education and Science* (Journal of Laws of 2022, item 574, as subsequently amended, and Journal of Laws of 2023, item 742, as subsequently amended).

Taking into account the PhD candidate’s excellent academic record, supported by high-quality publications in leading journals and conference proceedings, as well as the original methods employed to address the research problem, I hereby request that his doctoral thesis be awarded a distinction.

(Waldemar Minkina)