Review of a Doctoral Thesis at FIT BUT

Doctoral thesis (hereinafter referred to as "thesis"), title of the thesis: On-the-fly compression in time-domain ultrasound simulations

Name of the doctoral student (hereinafter referred to as "student"), name and surname: Petr Klepárník

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Name and institution of the reviewer (full name of the reviewer, full name and country of the institution): Łukasz Fura, Institute of Fundamental Technological Research Polish Academy of Sciences, Poland

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Please state your opinion on the following aspects of (I) the student's thesis and (II) the student's overall achievements, and (III) state your conclusion (a minimum of approx. 300 characters foreach item below is recommended):

I. Thesis

Appropriateness and relevance

Is the area addressed by the thesis appropriate to the particular scientific discipline of the thesis and does the thesis address relevant problems within the chosen area?

The reviewed dissertation is about the method of data compression in ultrasonic wave propagation simulations (in particular, it relates to the HIFU – High-Intensity Focused Ultrasound), so the topic of the work is in agreement with the scientific discipline of Computer Science and Engineering, to which this dissertation belongs. The work *On-the-fly compression in time-domain ultrasound simulations* is related to the specific problem of processing HIFU ultrasonic simulation data with large (more than a few or even several centimeters) physical space size and relatively high nonlinearity which translates into a significant number of nodes in the calculation. In his work, the student uses a toolbox k-wave for Matlab, which is widely used in the scientific community related to ultrasound, especially ultrasound with therapeutic applications, and based on this tool, he developed a method for data compression in ultrasound simulations related to HIFU in the k-wave toolbox.

A summary of the contributions of the thesis

From your point of view, please summarize what the goal of the thesis is, what the main contributions of the thesis are, and whether the thesis has achieved the chosen goal.

Please indicate also specific contributions of the student.

The goal of the dissertation was to develop a method for compressing online data in the time domain in ultrasound simulations and, more specifically, in HIFU simulations using the k-wave toolbox. The

aforementioned data compression method had to meet several important conditions, from the point of view of practical use:

- significantly (more than 90%) reduce the amount of necessary disk space for use in simulations,

- the results after reconstruction of the compressed data must be comparable from the point of view of the application which is HIFU simulations to the results in the case of uncompressed data,

- the computation time and the level of RAM required to be consumed during computation should remain approximately the same as for the uncompressed method.

In his work, the student addressed the significant problem of the substantial consumption of disk space in numerical simulations of the clinical application of HIFU. Various types of known lossy and lossless compression methods for signals were presented in the dissertation, but none of the methods met the above-mentioned requirements. For this reason, the student developed a HIFU compression method (HCM) and then applied it to on-the-fly calculations along with the use of 40-bit encoding of complex coefficients. In Chapter 5, it was proven that the developed HCM method satisfies the requirements mentioned above. An article on the developed method was published in the international journal *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control in 2022 with WoS=3.267 (2021), JCI percentile 76.25 (2021)*, which emphasizes the relevance and innovation of the method developed by the student.

Novelty and significance:

Please assess the level of novelty of the results and their significance for the given scientific area, for its further development, and if applicable for possible applications in practice.

The student in the dissertation solved an important problem from the point of view of mainly numerical simulations of the clinical application of HIFU. Reduced consumption of disk space resources in HIFU therapy simulations may in the future result in an increase in the quality of, for example, HIFU ablation anti-cancer therapy by performing numerical simulations of the HIFU ablation process specifically for a given clinical case, which may consequently also result in an increase in the quality of health care and thus in an increase in the quality, length, and comfort of people's lives. The student performed a literature review of the compression methods developed and applied the mentioned compression methods to the HIFU therapy simulation case. None of the methods met the previously assumed requirements, which were adjusted to the specifics of the case under study. The HCM method developed in the PhD thesis is characterized by novelty and can make a significant contribution to the scientific development of both high-performance computing (HPC) and HIFU therapy.

However, the work presented lacks a comparison of the two methods of calculating the volume rate of heat deposition (Q) mentioned by the student on page 16. The student developed the HCM method for the general case (equation 2.8), which, of course, by design alone should result in more accurate results than the second method (equation 2.9), which is related to the approximation of the propagating wave as a plane wave, although the second method is one that is also commonly used in the literature for nonlinear cases, including in reference [73] in the thesis. If I understand correctly, the use of the plane wave approximation excludes the need for the compression method proposed by the student, because

as the student writes on page 15 "The reason why the entire domain is stored rather than a small area around the focus is the aliasing that arises when calculating the divergence of the average intensity as the input to the thermal simulations, and the accuracy of the input is the critical parameter of usability/precision of the thermal simulations. ", and in this method, the divergence of the average intensity of the wave is not calculated, so that only a small and of interest fragment of the simulation results can be stored, which significantly reduces the consumption of disk space. The paper lacks an analysis of this issue, so I would ask the student to address the above-mentioned issue during the defense.

Evaluation of the formal aspects of the thesis:

Please evaluate formal qualities of thesis and its language level.

The work has 93 pages and is organized in a logical sequence. Throughout the first four chapters, the reader is introduced to the problems of the issue being addressed, namely ultrasonic simulations, signal compression methods, and signal compression quality evaluation. In the fifth chapter, the student presents the developed method and its verification. The last chapter is a summary of the work.

Below are some comments on the work:

- there were a few language errors in the work, e.g. page 10: "At low focused locations, it is possible to get up to 10 harmonic frequencies, but at highly focused locations. Up to 600 harmonics would be useful for accurate modeling of heat propagation."

- in the list of abbreviations (page 4) there was an error in the definition of CEM43 - it should be T = 43°C.

- not particularly significant, but introducing some confusion, is a formal error in the form of an out-of-order citation order in the paper's bibliography.

- graphs 2.2. on page 11 seems to me not to represent the same signal. The graph of the sound pressure signal over time and the signal spectrum are incompatible from the point of view of signal amplitude.

- The reference is missing the statement from page 9: "... but the most important issue and challenge is the precise placement of the ultrasound focus."

- page 10 - "To obtain a clinically relevant simulation, the grid sizes of 4096^3 to 8192^3 must be defined at least for 50 thousand simulation time steps [33, 72]." Where does the statement about such a large number of simulation time steps and such a large grid size come from? In the references, the maximum is given as 31876 time steps which is almost half of the given value. In addition, in the given publications the maximum grid size was:

- 1200 × 1200 × 1200 grid points in 2016 Nonlinear 3-D Simulation of High-Intensity Focused Ultrasound Therapy in the Kidney

- 4096 × 2048 × 2048 grid points in 2016 Full-wave nonlinear ultrasound simulation on distributed clusters with applications in high-intensity focused ultrasound.

The comments made do not detract from the high quality of the dissertation, and despite the comments made, the work is readable and understandable in terms of the order in which the topics are presented as well as in terms of language.

Quality of publications

Has the core of the thesis been published at an appropriate level? Please judge the quantity and quality of the publications. When judging the quality, please take into account internationally recognized standards (WoS/Scopus quartiles, CORE ranks, specific knowledge of flagship publication channels of agiven community, etc.) in a way appropriate for the given area of the thesis.

An article on the developed HCM method was published in the international journal *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control in 2022 with WoS=3,267 (2021), JCI percentile 76.25 (2021)*, which demonstrates the significant relevance and innovation of the presented issue and the developed method. Other works directly related to the dissertation were published in 2018 in the journal *Information* with *SJR=0.624 (2021), JCI percentile 48.17 (2021)* and in the *IEEE International Symposium on Signal Processing and Information Technology (ISSPIT)* in 2017, *CORE=C*. I consider the number of articles published by the student related to the dissertation to be sufficient, and the quality of the papers increases with the development of the topic to the level of very good journals (*JCI percentile 76.25 (2021)*).

II. Student's overall achievements

Overall R&D activities evaluation:

Does the student's thesis, the results included into it, and possible other scientific achievements listed in the list of scientific activities indicate that he/she is a person with scientific erudition and creative abilities?

The overall experience presented, the publications and the results of the student's dissertation clearly indicate his significant creative abilities and scientific erudition. The student has published articles at the intersection of acoustics, biomedical engineering, medical imaging and computer processing, which demonstrates the interdisciplinary knowledge the student possesses.

Assessment of other characteristics (optional):

More characteristics of the student may be added here (e.g., awards, grant participation, international collaboration, etc.).

III. Conclusion

In conclusion, the presented work *On-the-fly compression in time-domain ultrasound simulations* is a thesis of high scientific quality being an important contribution to the scientific community and possibly in the future to clinical practice. The student has published articles on the dissertation topic in international scientific journals of significance.

In my opinion, the thesis and the student´s achievements until now meet the generally accepted requirements of the proceedings leading to PhD title conferment (in accordance with Section 47 of Act No. 111/1998 Coll., on higher education institution).

Warsaw 16.10.2023

Signature of the reviewer: