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Łódź, 20 March 2026

Review of the Doctoral Dissertation
MSc. Eng. Shivangi Sachar
entitled:
Performance and Noise Sources of a Savonius Wind Turbine in an Urban Environment

1. Formal basis for preparing the review

The basis for preparing this review is the letter dated 18 December 2025 from Dr. hab. inż. Grzegorz Żywica, associate professor of IMP PAN, Deputy Director for Scientific Affairs of the Szewalski Institute of Fluid-Flow Machinery, Polish Academy of Sciences (IMP PAN), along with the attached doctoral dissertation by MSc. Eng. Shivangi Sachar entitled "Performance and Noise Sources of a Savonius Wind Turbine in an Urban Environment". The dissertation was prepared at the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences. The supervisor of the PhD thesis is Prof. Dr. hab. inż. Paweł Flaszyński.

2. Characteristics and assessment of the relevance of the dissertation topic

The doctoral dissertation presented for review examines the performance and noise sources of a Savonius wind turbine in relation to the application of this type of turbine in an urban environment. The scope of work carried out by the Doctoral Candidate is extensive. It includes studies related to the assessment of wind conditions in selected locations in England and Poland; experimental investigations of various Savonius turbine configurations on test stands at the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences and at Delft University of Technology; numerical simulations of flow through the turbine; as well as examinations of Savonius turbines under real operating conditions.

Currently, significant attention is devoted to energy generation based on renewable energy sources. Despite numerous studies, the use of wind energy remains a highly significant research domain. One of the most challenging areas of wind energy application is urban environments. This results from both highly complex wind conditions in such areas and from the impact of operating devices on humans, including generated noise and aesthetic considerations. Taking these factors into account, the

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subject of the research presented in the dissertation can be regarded as timely and relevant from both a scientific and practical perspective.
The Doctoral Candidate focused on the study of a Savonius Vertical Axis Wind Turbine (VAWT). Despite its significant drawback of relatively low efficiency, numerous advantages of this turbine type become apparent in urban environments, including independence from wind direction, low start-up speed, relatively high torque, and the possibility of placing the generator at the base of the turbine. These turbines operate on the basis of drag force, resulting in low rotational speed, which contributes to low emitted noise levels, making them an attractive option for urban settings. The issue of noise generated by the Savonius rotor has not yet been thoroughly investigated, which provided the Doctoral Candidate with an opportunity to meaningfully broaden the existing knowledge in the field.
The dissertation includes a range of aspects related to experimental research, analysis of the obtained data, and flow simulations. For these reasons, the subject matter of the reviewed dissertation lies within the field of engineering and technical sciences, specifically within the discipline of mechanical engineering.

3. Description of the dissertation's content, its substantive assessment, as well as questions and remarks

The doctoral dissertation is written in English. It comprises 177 pages and is divided into six main chapters, which are further subdivided into numerous subchapters and sections. These are preceded by abstracts in both English and Polish, as well as a list of symbols, and followed by three appendices. The dissertation concludes with a bibliography containing 227 literature sources.
The dissertation is written in an accessible and generally correct language; however, there are numerous shortcomings related to vocabulary, terminology, descriptions, and notation. A fully consistent system of symbols is lacking. The list of symbols includes only a portion of them; for some, units are provided, while for others they are not. All these shortcomings hinder, though do not prevent, a proper understanding of the work.

Chapter 1, "Introduction", presents a literature review of the key aspects related to the dissertation. As always, this poses a challenge to the author in terms of providing a concise but precise discussion of the state of the art. The author discusses the most important aspects relevant to the study.
The chapter begins with a presentation of the motivation for the research in the context of using small wind turbines in urban environments, highlighting the specific features of vertical axis wind turbines that make them suitable for this application. Types of wind turbines are presented, with emphasis on VAWTs. Since the dissertation focuses on the Savonius turbine, a more detailed description of its operating principle is missing. The very brief explanation on pages 7 and 8 is clearly too general and does not illustrate the complexity and time variability of the flow around the Savonius turbine. This turbine is characterized by a complex flow pattern around its blades, with changes occurring during rotation that lead to varying pressures on the blades and around the rotor and, consequently, noise generation. Therefore, a clearer description of its operating principle, with improved graphical presentation and a more detailed explanation of the phenomena involved, would be advisable.

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The following sections present fundamental aspects related to wind energy and its conversion using wind turbines, as well as definitions of basic performance parameters. Particular attention is given to the specifics of urban areas and the discussion of using wind turbines in such environments. This also relates to the issue of noise generation associated with wind turbines. Overall, the literature review is broad and adequately presents the essential aspects of the discussed issues. It is unfortunate that this section does not provide reference numerical values for typical turbine performance (e.g., power coefficient values) and noise levels, which would give a better reference point for the discussion of results in subsequent chapters.

The chapter concludes with the presentation of the research objectives, which relate to the analysis of wind conditions in selected locations, experimental investigations of turbine performance and noise emissions on dedicated test stands, numerical simulations, and studies of innovative wind turbines developed at the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences.

The chapter contains numerous linguistic errors (e.g., capitalization error "savonius" written in lowercase); slang expressions (e.g., "turbine can rotate faster than wind"); missing references for Figures 1.1.4 and 1.1.5; errors in parameter notation (e.g., the symbol "m" in equations 1.2.1 and 1.2.5 does not denote the same quantity), errors in units (density on p. 12), etc. The very important power coefficient in Section 1.2.3 is referred to only in this section as "coefficient of performance". The descriptive formulas (1.2.13–14) presented on p. 16 are not appropriate for a doctoral dissertation. The information in Section 1.4.2 is essentially a repetition of the final part of the previous section. As mentioned above, these issues do not prevent understanding of the work, but the Doctoral Candidate should pay attention to such aspects when preparing the dissertation.

Not all aspects are discussed sufficiently clearly, which gives rise to several issues for broader explanation and some questions:

1. Since Savonius turbines are not widely used, specific information regarding their noise sources is limited. However, based on the flow structure around the Savonius rotor and typical noise sources described in Section 1.3.5, please characterize the phenomena responsible for noise generation in this type of turbine.
2. The first paragraph of Section 1.3.3 mentions locations "farm in vicinity of an urban setting or install wind turbines on building rooftops." It is not clear why this approach can overcome the mentioned challenges concerning noise, turbulence, etc.

Chapter 2, "Methods utilized in this thesis", presents an overview of the methods applied in the research conducted by the Doctoral Candidate. It begins with a description of methods used to represent the probability distribution of wind, focusing on the Weibull distribution and explaining methods for determining the shape and scale parameters. Other types of distributions are also discussed. The Doctoral Candidate presents all methods in a synthetic, mostly clear manner. However, despite relying on numerous sources, she did not fully unify the notation system. In several cases, explanations of symbols used in equations are missing, including in the key Equation

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2.1.7, presenting the gamma function, which plays an essential role in all the discussed methods.

The description of numerical methods is also concise. In my opinion, it clearly addresses the most important aspects of numerical flow simulations. The subsection dedicated to noise measurements also discusses this topic in a very compact yet clear way, covering measurements with a single microphone and, more interestingly and more thoroughly, acoustic imaging.

This chapter also contains numerous editorial errors. In many instances incorrect equation numbers are provided (particularly on pages 38 and 48); there are clear errors within equations (2.1.8, 2.2.3, 2.2.6) or mathematically imprecise expressions (2.2.10); uppercase and lowercase letters are used interchangeably in symbols (e.g., Equation 2.1.1); symbols used in equations are not explained (e.g., in the Navier–Stokes equations 2.2.2 and 2.2.3), etc. There is also an inconsistency in the numbering of sections—some subsections contain only a single numbered section without continuation (2.1.1; 2.2.1.1; 2.3.2.1). As in the previous chapter, this does not significantly hinder reading or evaluating the work, but the number of such shortcomings is considerable.

Despite these issues, I believe that the descriptions are adequate and sufficiently present the broad spectrum of methods applied in the research.

In this chapter as well, not all aspects are discussed with sufficient clarity, giving rise to several points requiring further explanation:

3. The description of k – shape parameter and c – scale parameter on page 36 is not clear. Some further illustrations are presented in Fig. 2.1.1, but a more precise description of the parameters would be recommended.
4. What is EPD mentioned on page 41?
5. Please elaborate more precisely on the issue of boundary conditions mentioned on page 46. Does this also refer to the size of the computational domain?
6. The name of the turbulence model k–omega (M-SST) is unfamiliar to me. Is this the Menter model, or is it some modification? In Chapter 3.2, a different (typical) name is used: k–omega SST.

Chapter 3, "Performance analysis: Savonius wind turbine", begins with a broad and comprehensive literature review concerning the influence of various configurations and parameters of Savonius turbines on their performance. This review highlights the lack of unambiguous information regarding the effect of rotor segmentation on the maximum value of the power coefficient. Configurations of both single-segment and five-segment rotors subjected to numerical investigations are also presented.

The next subsection is devoted to numerical simulations of the flow around the Savonius rotor. The description of the numerical procedure is good and clear, except for the fact that it does not state upfront that the simulations are two-dimensional (2D). A definition of turbulence boundary conditions is also missing. The term "periodic steady state" used in the discussion of the results is imprecise in the context of a case where the torque varies during rotation. In the Grid Convergence Analysis, the reference [186] is cited; however, this source does not define the GCI in the manner presented in the dissertation. Simulation results for free-stream conditions are compared in Fig. 3.2.3 with results from publication [66], without addressing the fact that the obtained power coefficients are significantly higher than typical values for this type of turbine and are

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more characteristic of simplified 2D simulations. The same figure also presents results labelled as Experiment IMP PAN, but these results differ from those shown in Fig. 3.3.3. Since the experimental test stand at IMP PAN is not presented in the main body of the dissertation, it is not immediately clear, upon first reading, why investigations were performed for different distances from the wind tunnel outlet, nor why so much space is devoted to analysing results for rotor positions close to the outlet. The obtained results seem to suggest that placing the rotor at a distance equal to the width of the outlet channel (x = 1 m) is sufficient to ensure that the flow is not significantly affected by blockage. Unfortunately, the data presented in Fig. 3.2.6 and Fig. 3.2.3 are not shown together, which prevents a clear comparison. The explanations concerning the influence of blockage are generally correct, although some expressions referring to "pressure gradient", "augmentation in the thickness of this boundary layer alongside the rotor blades", and "increase in Turbulence Intensity" are not clear or not supported by the presented results.

The next subsection presents the results of experimental investigations. The results obtained are interesting, and the accompanying analysis explains the fundamental performance differences between the single-segment and five-segment rotors. However, several issues are not addressed. In the latter case, the data for different wind speeds (except for the lowest speeds) align along typical curves of the same shape. For the single-segment rotor, the data are quite scattered. Could this be influenced by data sampling? The description of the measurement setup and references to measurement uncertainty are missing. Although this may not change the overall interpretation, it could help explain the differences between the characteristics obtained for the two rotors. I also disagree with the statement on p. 78 that the values for position 3 are "slightly higher". They are significantly larger.

This chapter also contains editorial errors, such as incorrect references to figures (especially on p. 76) or sections.

As in the previous chapters, several aspects are not discussed with sufficient clarity, and therefore, I have the following questions and comments:

7. It is not clear whether the characteristics shown in Fig. 3.1.1 are from the author's own measurements or from literature sources. If they come from the latter, the corresponding reference is missing.
8. The data in Table 3.1.1 do not indicate an Aspect Ratio = 5. Is this a mistake in the table, or is AR = 4.4?
9. How were the boundary conditions for turbulence defined in the CFD simulations?
10. Please explain the differences between the results presented in Fig. 3.2.3, labelled Experiment IMP PAN, and those presented in Fig. 3.3.3.
11. Please present together the simulation results of the torque and power coefficients for the free stream and test section (x = 1) conditions, and discuss the differences.
12. In the simulations shown in Fig. 3.2.8, was the outlet boundary condition really set to 100 kPa? Such a value is not shown in the legend.

Chapter 4, "Experimental acoustics assessment of Savonius VAWT", begins with the presentation of research carried out on the test stand at IMP PAN. This investigation is

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based on point measurements of the sound pressure level. The description does not include the important information about the location of the rotor relative to the wind-tunnel outlet, which, given the results from the previous chapter, is crucial. Comparing the characteristics shown in Fig. 3.3.3 and Fig. 4.1.5, it appears that the distance used here is close to 0.28 m. This raises the question of why, for these tests, a location unrepresentative of typical turbine operation was chosen instead of the more appropriate one at x = 1 m.

The selected cases for analysis, motionless rotor, conditions of maximum efficiency, and free run, seem representative for comparing acoustic emissions of the single-segment and five-segment rotors. The results and their analysis indicate lower noise generated by the five-segment rotor, despite its significantly lower efficiency. However, the presentation and analysis of psychoacoustic parameters are unclear due to the lack of formulas defining these quantities and the imprecise descriptions.

Very interesting results are presented in the subsequent subsection devoted to acoustic investigations conducted at Delft University of Technology. A significant aspect here is the comparison of turbine performance with the generated noise. The results shown in Fig. 4.2.4 indicate a relatively low and constant noise level within the range of low TSR values, with a marked increase once the maximum efficiency is exceeded. The analyses provided explain this dependence well.

A considerable portion of the chapter is dedicated to the free-run case in which the rotor operates without a load. This is undoubtedly an interesting scenario, as the noise levels in such conditions are substantially higher than under optimal turbine operation. Nevertheless, it appears that this case dominates the analysis. Equally interesting, and potentially more important from the perspective of turbine application, are the conditions of its regular operation, for which the results are limited. A valuable element of the research is the noise source localization. As shown, the region close to the endplates is identified as the primary noise source. Interestingly, the noise generated by the blade is not located near its outer tip but rather closer to the axis. This is an important observation that may serve as a starting point for further investigations. On the other hand, the rear region of the rotor was not examined, so it is not clear whether the complex flow structures in this zone may, in fact, be a dominant noise source.

There are several unclear aspects in this chapter. It is not explained why the analysis focused on the frequency range 600 Hz to 6 kHz. Moreover, the data shown in Fig. 4.2.6 are not clearly described or analysed. The Power Spectral Density is not defined here nor in Appendix A.

Based on the presented information, several questions arise:

13. Why was the location used in the IMP PAN tests chosen, even though it is not representative of typical turbine operation? Why was the more appropriate location at x = 1 m not selected for the tests?
14. How should the statement "with single-segment rotor generating 13.8 times more acoustic energy than the five-segment rotor" (p. 86) be interpreted?
15. Which formulas define the parameters presented in Fig. 4.1.6? They are not included in this chapter nor in Appendix A, where only their descriptions are given.
16. Why did the analysis at TU Delft focus on the frequency range from 600 Hz to 6 kHz, while lower frequencies within the BPF (Blade Passing Frequency) range

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were omitted? How would frequencies below 600 Hz affect the Overall Sound Pressure Level?

17. Unfortunately, the microphone array was positioned only to observe the frontal part of the turbine. What was the reason for not also relocating it to observe the rear side?

Chapter 5, "Analysis of urban environment and wind turbines", begins with an assessment of wind conditions in several locations in England. Based on the measurement data, the Doctoral Candidate compared various Probability Distribution methods for the selected locations, identifying the Weibull distribution as the one that best fits the measurement data. Different methods described previously in Chapter 2 were used to determine the distribution parameters. While the choice of the Weibull distribution is well justified, a clear explanation is missing regarding how differences between the methods used to estimate the model parameters affected the quality of the predictions. Although each of the analyses is illustrated fairly clearly, the continuous switching between different locations and different timescales (from 1 to 4 years) hinders readability. It would be useful to organise the data more systematically and present it in a more consolidated manner.

It is not elaborated why the QR6 turbine has such high electrical power compared with the other turbines. The influence of turbine size is obvious, but turbine efficiencies are not provided in Table 5.1.1, so the impact of this factor is not visible. Has the turbine already been installed, and if so, are there data from real operation confirming its performance?

In the case of the wind condition assessment for two locations in Poland, the measurement period was limited to only a dozen hours (~18 hours), which, as the Doctoral Candidate herself noted in previous chapters, does not allow for determining the wind potential at these locations. No explanation is given as to why only such a short period was analysed. The presented results supplement the Doctoral Candidate's methodological approach to some extent, e.g., regarding turbulence intensity estimation and the indication of how the best method for determining the Weibull parameters is selected.

Perhaps the choice of a short period of wind measurement is related to the turbine performance studies described in Chapter 5.2, where measurement results are shown for two innovative turbines developed at IMP PAN and installed on its building and on the hill in Przywidz. For a clear understanding of the results, the dissertation should include power coefficient characteristics as a function of TSR for these turbines. The descriptions provided suggest that their peak efficiency may occur at TSR > 1.0. The results indicate low efficiency of converting wind energy into electrical energy, which under real conditions was only 7%. A low generator efficiency and a high variability of wind speed may explain these values, but the generator characteristics are not provided, and the analysis on p. 129 with peak reduction (Fig. 5.2.14) is unclear.

While the plots in Fig. 5.2.5 and 5.2.6, showing relations derived directly from the obvious dependencies between turbine power, wind speed and rotor speed, seem unnecessary, the presentation of similar lines in Fig. 5.2.11, combined with coloured operating points for different TSR values, allows for extracting interesting conclusions

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about the optimal TSR range. Also, the correlation between wind speed variations and rotor tip speed variations provides very interesting insights.

The prototype turbine installed in Przywidz is particularly interesting, and due to its different rotor configurations and the use of separate generators for the lower and upper Savonius-rotor sections, it offers potential for extensive and insightful research. The dissertation presents only basic results for a short time interval, essentially repeating the analysis done for the turbine located on the IMP PAN building. Information about the recorded average efficiency and the potential influence of different rotor configurations on performance is missing.

This chapter also contains editorial errors, such as a mistake in Fig. 5.1.6 regarding the power unit; an excessive number of significant figures in Table 5.1.4; an extraneous text in Table 5.1.6; missing details in figure captions (location, timespan); several surnames and locations written in lowercase, etc.

Analysis of the presented information raises several questions and remarks:

18. Chapter 5.1 does not precisely discuss the measurement location, including the height at which wind-speed data were collected. I understand this corresponds to the height planned for turbine installation? The equipment used and the measurement uncertainty are also not specified.
19. Under what assumptions were the results shown in Fig. 5.1.6 obtained? Was a constant efficiency assumed, or was it dependent on wind speed and possibly other factors?
20. Why was the analysis for the IMP PAN and Przywidz locations limited to less than 24 hours of data? What is the usefulness of such a short dataset for determining wind conditions at these locations?
21. I do not understand the reference to Fig. 5.1.5 (Clifton location) when discussing the determination of the shape and scale factors for the IMP PAN data.
22. For what reasons would the cost of the IMP PAN turbine be significantly lower than that of a classical Savonius turbine of identical dimensions (p. 121)?
23. What is the purpose of using separated rotors in a one-line configuration? Is there any benefit to this arrangement?
24. Much is written about power-extraction algorithm improvement. Was any work actually performed on this issue? What modifications of the algorithm would the Doctoral Candidate suggest to improve efficiency?

Chapter 6, "Conclusions and future work", provides a concise and clear summary of all the studies presented in the dissertation and outlines the most important conclusions resulting from the conducted research and analyses. In light of the investigations described in the thesis, the conclusions presented here do not raise substantial concerns. The proposed directions for future work are interesting, and their pursuit will undoubtedly enhance the state of knowledge regarding the operation of Savonius turbines, in particular, the innovative turbine developed at IMP PAN. From my perspective, it would be valuable to conduct more extensive research similar to that performed at TU Delft and correlate it with high-quality 3D simulations. This would allow for more precise identification of noise sources characteristic of this type of turbine.

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The Doctoral Candidate defined an interesting research hypothesis: "The integration of wind energy into urban environments necessitates specific turbine characteristics that must be addressed to ensure their acceptance from both environmental and social perspectives." In my opinion, based on the comprehensive literature review, this thesis has largely been confirmed. Moreover, part of the research conducted by the Doctoral Candidate, particularly the noise measurements and their results analysis, fits well within this hypothesis from the environmental point of view. What I find missing, however, is a clear reference to the social perspective.

The dissertation features numerous positive aspects. A strong positive point is the literature review covering a wide range of issues discussed in the thesis. In most cases, the analysis was appropriately in-depth for a doctoral dissertation. The scope of the research presented is also very broad, encompassing the assessment of wind conditions in selected locations, experimental investigations of the aerodynamic performance of Savonius rotors, acoustic studies, particularly those conducted at TU Delft, real-world turbine testing, and simplified yet interesting numerical simulations of the Savonius rotor.

A negative aspect is the considerable neglect of the editorial side of the work, which is unexpected in a doctoral dissertation. Some descriptions and analyses are also not sufficiently clear or in-depth, which explains the significant number of my comments and questions. On the one hand, I am pleased that my contribution to Savonius turbine research has been recognised, but on the other hand, this highlights an editorial shortcoming—namely, the same article being listed three times in the bibliography ([32], [38], [185]).

The comments and errors noted above do not reduce the overall readability of the dissertation and do not significantly affect the positive evaluation of the substantive merits of the work.

4. Evaluation of the dissertation and final recommendation

Evaluating the dissertation as a whole, I find that MSc. Eng. Shivangi Sachar has demonstrated solid general theoretical knowledge within the discipline of mechanical engineering, enabling her to carry out a comprehensive literature analysis and a sufficiently in-depth examination of the various aspects of the Savonius wind turbine operation, taking into account the perspective of its application in an urban environment.

In conducting her research, the Doctoral Candidate employed an appropriate and broad scientific methodology, encompassing experimental and numerical methods as well as aspects of data processing and analysis. The obtained research results and the conclusions drawn from them, especially those related to the levels and sources of noise generated by Savonius turbines, allow me to conclude that the scientific problem has been addressed in an original way that enriches existing knowledge. They demonstrate also the Doctoral Candidate's ability to conduct independent scientific work. The critical remarks presented in this review, primarily concerning editorial issues and certain aspects requiring further discussion, do not fundamentally diminish the merit of the dissertation.

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Taking into account the scientific, cognitive, and practical value of the work, I state that the doctoral dissertation submitted for review, "Performance and Noise Sources of a Savonius Wind Turbine in an Urban Environment", meets all the requirements set for doctoral theses under the Act on Higher Education and Science of 20 July 2018 (Journal of Laws 2023, item 742, as amended). Therefore, I recommend that the dissertation by MSc. Eng. Shivangi Sachar be admitted to public defence.

In Polish:

Biorąc pod uwagę wartość naukową, poznawczą i aplikacyjną rozprawy stwierdzam, że przedstawiona od oceny rozprawa doktorska „Performance and Noice Sources of a Savonius Wind Turbine in an Urban Environment", spełnia wszystkie wymagania stawiane pracom doktorskim przez obowiązującą ustawę Prawo o szkolnictwie wyższym i nauce z dnia 20 lipca 2018 r. (Dz.U. 2023 poz. 742 ze zm.). Wnioskuję o dopuszczenie rozprawy MSc. Eng. Shivangi Sachar do publicznej obrony.

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