**Final technical report on Project K 129023 “Elaboration of new methods for noise mapping of ducted axial fans”**

## 1. Outline

The objectives of the Project, organized into interacting subprojects, are summarized as follows.

- New analytical, semi-empirical and experimental guidelines were aimed to be established that are to be incorporated in the design of new, market-competitive, aerodynamically efficient low-speed ducted axial fans of low noise emission. These objectives were achieved within the *„Wind tunnel + Silent free jet” subproject*, as well as within the *„Evaluation” subproject*.
- The Phased Array Microphone (**PAM**) technique, together with the related beamforming technology, was aimed to be further developed and extended for offering economical (low-cost) and yet technically effective, competitive solutions for case-specific inspection of internal noise sources, customized to the cylindrically ducted fan geometry. These objectives, fulfilled within the *„Annular PAM” subproject*, enable new, feasible and reliable PAM installations and data processing schemes for fan laboratories and industries (factory test facilities, industrial on-site studies). The Project Team has become capable for designing and realizing customized PAM systems, matching user-specific demands.
- The experimental database of the recently developed concept of the acoustically transparent and aerodynamically yet impermeable „observe-through-the-duct” layout was aimed to be extended with experiences on real industrial fan installations. These objectives, fulfilled within the *„Acoustically transparent duct”* (**ATD**) as well as the *„Evaluation” subprojects*, uniquely serve for carrying out comprehensive studies on the *in-duct* noise sources observed *from the outside*, i.e. *through the duct*, to be offered by the Project Team for the community on fan research, development and innovation (**RDI**), as well as for acoustics-based condition monitoring (**ABCM**) on industrial sites.
- The methodology of beamforming for processing PAM results, as well as processing and evaluation of the output data of acoustic imaging, were aimed to be further developed, and the evaluation experiences were intended to be widened, in order to enable a more comprehensive engineering evaluation in basic research on the detected noise sources. To this end, new evaluation methods were introduced and refined, as well as the experiences were broadened, within the *„Evaluation” subproject*. These activities have made the Project Team capable to offer services related to acoustics analysis to RDI institutions and industries over a broad range, customized to user demands. Being beyond the original scope of the Project, the “Evaluation” subproject was expanded to Industry 4.0 aspects, with the envisaged aerodynamic, vibration and acoustic monitoring of Smart Fans, incorporated in systems of Smart Ventilation, serving for Smart Factories.
- In addition to experimentation, the Project aimed at complementarily involving simulation techniques of Computational Aeroacoustics (CAA) and Computational Fluid Dynamics (CFD), for in-depth comprehension of the underlying physics of noise sources, and for discovering the links between noise and flow mechanisms. The computational experiences were broadened within the *„Simulation” subproject*, significantly widening the capabilities of the Project Team to offer RDI services for customers.

In what follows, the definite project achievements are reported in more detail, included within the subprojects as separate items. The publications acknowledging the support by the Project in most cases, and elaborated / being under elaboration within the Project, are specified at the end of the report, and are referenced in the text.

## 2. „Wind tunnel + Silent free jet” subproject

2.1. Using wind tunnel experiments, ***novel empirical correlations*** were established [1-2] and refined [3] ***on the lift and drag coefficients of low-Reynolds-number plate blades of circular arc camber line***. Since cambered plates are superior to classic airfoil profiles – providing higher lift and higher lift-to-drag ratio – for chord-based Reynolds numbers below ~$10^5$, these correlations enable the design of aerodynamically efficient, competitive new low-speed fans of low blade solidity.

2.2. Via wind tunnel experiments on stationary basic models of fan blades, a ***semi-empirical model*** was elaborated [1], refined [4], and extended [5-6], as a design tool for consideration of ***dominant frequency of fan noise and blade vibration caused by profile vortex shedding***. By such means, the frequency of vortex-induced noise and vibration can be forecasted, and its harmfulness can be moderated / eliminated already in the preliminary blade design phase. The modelling aspects of profile vortex shedding in fans were analysed [7], and, on this basis, the semi-empirical model was applied to ***design case studies*** [8-9] of ***fan rotors with cambered plate blades***, aiming at ***avoiding human annoyance*** by noise as well as ***reducing the risk of blade resonance***.

2.3. A ***minimal model*** was developed [10-11] for description of the ***vortex-dominated blade wakes and their dispersion*** downstream of the trailing edge. This model makes possible a straightforward but effective design characterisation of blade row interaction – e.g. ***rotor-stator interaction*** in ducted fans –, and provides a design tool for forecasting the frequency broadening of the ***tonal noise of interaction***. Furthermore, the model gives a means for ***characterisation of vortex motion within the wake***, contributing to the design ***modelling of vortex-induced noise***.

2.4. As supplement to the experiences obtained on basic blade models exposed to *wall-bounded jets*, i.e. *wind tunnel experiments*, the ***PAM-related experimental database on noise characteristics of basic blade models*** was extended using a ***silent free jet*** [12]. Such database is serving for refinements in design consideration of blade noise.

## 3. „Evaluation” subproject

3.1. The acoustic experiences on stationary blade models in Section 2 were expanded to real fan rotors. The PAM data obtained on an industrial fan rotor were evaluated in a comprehensive manner, enabling the ***extension of the semi-empirical model available in the literature to rotors of low-speed, low-Reynolds-number fans of cambered plate blades*** [13]. The extended model makes possible the preliminary design consideration of turbulent boundary layer-trailing edge noise, together with blade redesign efforts for noise reduction.

3.2. The aeroacoustics aspects of fluid dynamics interaction between the fan inlet and the rotor were investigated via PAM measurements, and were evaluated in the context of supplementary CFD studies. ***A design proposal was given for noise reduction by appropriately selecting the inlet geometry, for suppressing the noise related to double leakage through the tip gaps*** [14]. As a supplementary study, the effect of duct diameter changes with involving CFD was investigated in [15].

3.3. Various ***data processing and evaluation techniques were developed, tested and documented*** for customized, comprehensive engineering evaluation of ***PAM-based beamforming data***. Such techniques include the following: ***clustering*** for localization of broadband noise sources [16]; ***filtering*** techniques [17]; principal component analysis, ***Proper Orthogonal Decomposition*** [18-19].

3.4. The ***Rotating Source Identifier*** (**ROSI**) ***methodology*** for processing the PAM data was ***further developed, expanded, and customized to various applications***, such as localization of rotating coherent sources [20], investigations at an angle with respect to the axis of rotation [21], processing data available in segments [22], processing of asynchronous PAM measurements [23]. Since the ending period of the Project focussed on the last topic [23], resulting in significant improvement in the noise source localization, it deserves a more detailed description herein. Beamforming maps are often hard to understand due to the presence of sidelobes, which can easily be confused with true noise sources. The level of the sidelobes can be decreased if more microphones are built into the array. However, this leads to the increase of the cost of the measurement equipment. In the case of steady investigated processes, increasing the number of microphones can be exchanged by carrying out asynchronous measurements. The individual measurement results can be combined during data processing in order to improve the obtained beamforming maps. Two studies have been carried out in the past year using asynchronous microphone array measurements. In the first, two point-like sources and an axial flow fan have been analysed using a 24-microphone array. In the second study, the number of microphones has been pushed to its possible reasonable lower limits. The array of reduced number of microphones, referred to also in the "Annular PAM" subproject, consists of 8 microphones only, and the asynchronous measurement technique has yet been successfully applied using this array.

3.5. ***Evaluation techniques*** were developed and refined for the ***comprehensive, PAM-based investigation of broadband noise sources*** associated with ***fan rotors*** and the related equipment [24-28].

3.6. ***Techniques*** for ***comprehensive, PAM-based studies of narrowband noise sources*** related to ***fan rotors*** were also elaborated and refined [29-32].

3.7. In order to foster the industrial utilization of experiences of the Project, the scope of the research was extended to ***Industry 4.0 aspects***, incorporating Smart Fans in Smart Ventilation serving for Smart Factories. ***Guidelines*** were established for ***condition monitoring for Smart Fans and the connected Smart Systems*** [33], specifying envisaged candidates for Smart axial fans [33] as well as Smart radial fans [34]. ***Preliminary case studies were reported on vibration studies as well as ABCM*** related to axial fans [35] – also involving the ATD technique –, and related to radial fans [35-36]. With consideration of the related experiences of the Project, the ***future perspectives and conceptual design of Smart Ventilation*** were discussed with members of the international turbomachinery community in a Workshop at the ETC15 conference [37].

## 4. „Annular PAM" subproject

Due to its high demand of purchasing and treating new hardware elements, this subproject suffered a significant delay due to the pandemic and economics crisis. By means of extending the timeframe of the Project, most of the difficulties were overcome. The functionality of the printed PAM circuit boards has been achieved. In order to extend the departmental PAM designing and building capabilities, a planar prototype PAM was developed, and qualification measurements were carried out for assessing the reliability of the in-house equipment. For a successful "hot test" of its portability and functionality, the new in-house PAM was taken by the research group to Karlsruhe Institute of Technology for a short-term research campaign (bilateral DAAD project).

The feasibility of applying a PAM with microphones of reduced number was surveyed. The resultant PAM was successfully applied recently on the site of an industrial partner for analysing the noise of a pneumatic quick-release valve.

The above advancements encouraged the Project Team to continue with the development of the hardware for the annular microphone array. The array has been built, and calibration measurements have been carried out. The annular PAM has its microphones located around a circle, while the centre of the array is not filled, allowing it to be placed around ducts. This feature has been taken advantage in a case study on investigating a ducted axial flow fan. The fan was previously extensively measured in an unducted configuration; however, the annular PAM and the acoustically transparent duct (ATD) facilitate ducted fan measurement as well. These measurements form the essential part of an acoustic and aerodynamic study carried out on the measurement fan in ducted operating conditions [38].

The above are summarized by such means that the Project Team has gathered ***skill and experience for designing, in-house building, testing and purposefully applying PAMs, including annular ones, that can be customized to various research demands and ducted fan installations***. The related activity has been documented in [38].

## 5. „ATD" subproject

This subproject aims at enabling the survey of acoustics associated with the fan – covered by casing and ductwork – from the outside, with incorporation of an ATD section. As preliminary study, the effects of the installation circumstances of the in-duct fan were surveyed [15].

Data gathered in ATD-related former measurement campaigns have been evaluated. The test facility was supplemented with additional ATDs to increase the investigated range of operation of the ducted fan. Further off-axis planar PAM measurements were carried out and the measurement results were evaluated. The results are concluded in [39]. A further measurement campaign has been carried out utilizing the annular microphone array [38].

The acoustically transparent measurement technique was further developed for radial fans. A wall section of the housing of the radial fan was replaced with an acoustically transparent wall section. Test measurements were carried out with the planar PAM at Karlsruhe Institute of Technology (as a part of a bilateral DAAD project). The evaluation of these measurement data is the basis for further research.

The ATD technique has been conceptually designed [33] and exploited in a preliminary case study [35] for utilizing the ABCM technique in an Industry 4.0 perspective.

The above are summarized by such means that the Project Team has gathered ***skill and experience for applying the recently developed ATD technique for ducted axial fan as well as radial fan RDI, and for fan condition monitoring (ABCM) purposes.***

## 6. „Simulation" subproject

The ***method development, preliminary studies, application, and comprehensive, concerted evaluation of data of CAA and CFD techniques***, customized to the Project topic, supported several segments of the Project, together with analysis of measurement results. Computational simulations were applied to support and enhance the subprojects, as well as fostering the engineering evaluation of the project outcomes, in the following manner. The utilization of CFD studies enabled a thorough and comprehensive exploration of rotor aerodynamics [14-15][38][41] within a ducted configuration. Examples for simulation activities are as follows: computational aeroacoustic investigation of airfoil cascades [40]; unsteady tip leakage flow analysis in the context of noise generation [41]; comprehensive analysis of flow phenomena at the inlet [14]; CFD studies on the in-duct installation circumstances of fans [15]; studies on the near-blade-tip phenomena from an aeroacoustic perspective [38].

The methodological development of evaluation techniques [22-23] was enriched by the inclusion of ***acoustically simulated noise sources***.

***Simplified two-dimensional CFD preliminary studies were carried out on rectilinear models of blade profiles representing low-speed axial flow fans.*** On the one hand, the concerted numerical and experimental evaluation of the simulation results aims to facilitate a ***deeper understanding of the vortex shedding phenomenon***. On the other hand, it provides further ***validation of the elaborated minimal model*** [10-11] allowing for simplified, cost-effective aerodynamic simulation of blade wake phenomena, incorporating vortex shedding effects.

## 7. Overview of publications

In the Project Plan, the following publication activities were altogether undertaken:

- 2 journal papers in Hungarian;
- 7 international conference papers;
- 5 WoS journal papers.

The publications realized (accepted or published) during the entire Project are as follows:

- 4 conference papers in Hungarian [18][24][29-30];
- 15 international conference papers [4-5][8][10][15][17][20-21][27][33-37][41];
- 2 journal papers in English without impact factor [19][40];
- 14 WoS journal papers [2-3][6-7][9][11-14][22][25-26][31][39];
- 2 other items [1][16].

Therefore, the publication activity within the Project meets the expectations well.

## 8. Industrial utilization; networking; domestic and international partnerships

Negotiations were carried out and are ongoing with manufacturers of fans and air technical equipment for indirect and direct industrial utilization of the project results.

For Hungaro-Ventilator Ltd., certain low-speed ducted axial fans of cambered plate blades [33] were redesigned for improved efficiency for given operating regimes. The achieved gain of 2 to 3 % of total efficiency enabled the fan manufacturer to equip the fans with electric motors of one class lower nominal power, thus reducing the cost and weight – and thus increasing the market competitiveness of the fan units. The manufacturer emphasized that such efficiency improvement is also beneficial for the industrial fan users as a contribution to fulfilment of Energy Efficiency Obligation Schemes. Solutions were elaborated for ducted axial fans enabling a sound power reduction up to 6 dB – e.g. utilizing an appropriate inlet bellmouth [14] –, and were communicated toward the potential industrial customers. In a separate RDI project, utilizing the experiences of the present one, a high-specific-performance, low-speed radial fan family was developed for Ventilation Works Ltd. incorporating straight plate blades and yet having a total efficiency as high as 80 % [34][36]. The test fans were inspected by PAM, for a redesign treatment of the major noise sources. The relatively low blade tip speed enabled relatively silent fan operation for the new fan family. The project experiences and results were further developed toward Industry 4.0 perspectives, establishing the Smart Fan concept for all the aforementioned fans as Smart Fan candidates [33][36], optionally including in-line flowmetry developed by the Project Team for Hungaro-Ventilator Ltd. [33], and incorporating acoustics-based condition monitoring (ABCM) aspects [35-37]. The developed, integrated in-line flowmeter increases the axial extension of the fan unit only by ~ 0,5 duct diameter, thus making possible the realizetion of compact Smart Fans of limited space demand. For DAAL-CON Ltd., preliminary studies were carried out on ABCM in a separate but related project, and the ductwork connected to the fan was redesigned, enabling an 8 dB reduction of overall sound pressure level in the human residence zone [35]. For 3B Hungaria Ltd., a proposal was elaborated for inclusion of Smart Fans and Smart Ventilation in the air technical separation process of municipal waste processing.

As networking activity, Smart Ventilation workshops were organized by the project team at the CMFF’22 and ETC15 international conferences [37], for popularization of the project results toward the international turbomachinery community, including potential industrial partners. Proposals have been made by the Project Team toward international partners via Expertise Offer datasheets for establishing EU projects (e.g. HORIZON-CL5-2023-D4-01-01, EU Twinning).

The collaboration (concerted laboratory actions, consultation) with foreign universities has been strengthened in the project topic (University of Rome „La Sapienza"; Otto-von-Guericke University in Magdeburg; Karlsruhe Institute of Technology; Friedrich-Alexander-University in Erlangen-Nürnberg.

The project results, after suitable further development, modification and extension, are foreseen partially to be exploitable also for propulsion systems being the subject of the ongoing K 143204 Project "Concerted acoustic and aerodynamic analysis on unmanned aerial vehicles".

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