PROJECT NKFI K 112277

“Further development of a phased array microphone-based diagnostics method for aiding in the noise and loss reduction of axial flow fans”

FINAL TECHNICAL REPORT

In the Technical Report, the own publications elaborated within the framework of the project, listed at the end of the Report in approximate chronological order, are referred to. These publications cite the recent international technical literature representing the State of the Art in the project topic, thus supporting the novelty content and the technical merit of the project results.

The content of Technical Report is in accordance with the workflow described in the originally submitted Workplan.

1. PROJECT TARGETS, PRACTICAL RELEVANCE

By considering each accomplished workphase in the Workplan, and viewing the entire timespan of the project, the project targets have been specified as follows. The activities carried out during the project have fulfilled the originally set project objectives in a re-structured manner.

1.1. Extension of semi-empirical modelling of noise emission of realistic low-speed fan rotors

Low-speed axial fans are widespread in industrial ventilation (e.g. cooling fans in technological processes), in building service engineering for residential and non-residential buildings (e.g. fans for heating, ventilating and air conditioning), as well as in equipment operating in the vicinity of humans (e.g. computer processor cooling fans, refrigerator fans, cooling fans of electric motors driving household or building service equipments). As such, the moderation of noise emitted by these fans is an important topic already in the design phase. The Reynolds number calculated with the rotor blade chord and the relative flow velocity is considered herein. The aforementioned fans are often of relatively small size and / or are often operated at moderate speed, e.g. due to rotor speed control. As a result, the Reynolds number is relatively low, often characterized by the orders of magnitudes (**o.m.**) of $Re = 10^4 \div 10^5$.

For forecasting rotor blade noise in blade design, the semi-empirical **BPM model** (Brooks, T. F., Pope, D. S., and Marcolini, M. A., 1989, Airfoil self-noise and prediction, *NASA Reference Publication 1218*) is often attempted to be used even in recent fan design campaigns. However, the BPM model is based on measurements on ***two-dimensional (2D)***, ***isolated***, ***stationary***, ***symmetrical uncambered airfoils,*** at ***Reynolds numbers*** of **o.m. ≥ 10^5**.

The present project has been aimed at empirically extending the applicability of the BPM model to realistic annular (three-dimensional, 3D) cascades of fan rotors, consisting of circular arc-cambered plate blades – used frequently in low-speed fans – for o.m. of $Re = 10^4 \div 10^5$. The extension of the semi-empirical model is based on spatially resolved Phased Array Microphone (**PAM**) measurements aiming at the upstream-radiated sound of a case-study fan.

The model extension makes possible the concerted aerodynamic-aeroacoustic design of low-speed axial fans for high aerodynamic efficiency (i.e. loss reduction at prescribed performance) and low noise, with involvement of empirical cascade correlations in preliminary design. At a prescribed aerodynamic performance, the sound power level reduction in the o.m. of 6 d*B* provides a significant competitive advantage on the fan market.

1.2. Study on noise-reducing appendages

For axial fans, quarter-circle inlet bellmouths are frequently used, providing simultaneous aerodynamic and aeroacoustic benefits for the fans. Such inlet bellmouths are proposed e.g. by the standard ISO 5801:2017 (*Fans. Performance testing using standardized airways*) for loss reduction. It is known from the technical literature that such inlet bellmouths have a potential of sound power level reduction in the o.m. of 6 d*B*. However, ***the literature lacks in describing the underlying flow physics of the noise reduction mechanism*** in a detailed manner.

The present project has been aimed at carrying out spatially resolved experiments on the upstream-radiated sound of a quarter-circle bellmouth entry + unducted fan assembly, incorporating various inlet bellmouth geometries, for comprehension, description, and quantification of the noise reduction mechanism dedicated to the bellmouth entry. Application of the spatially resolved PAM technique is inevitable in such experiments.

Such studies provide quantitative guidelines for purposefully assigning a quarter-circle inlet bellmouth, being suitable both aerodynamically (for loss reduction) and aeroacoustically (for noise reduction), to a given unducted fan. The sound power level reduction in the o.m. of 6 d*B* by means of the bellmouth inlet is again a potential task, thus enhancing the competitiveness of the fan on the market.

1.3. Objectivization and algorithmization of the PAM evaluation procedure

The results of PAM-based beamforming experiments are usually processed in the literature by ***subjective means*** (e.g. on the basis of visual inspection of the beamform maps), on the basis of ***subjective and arbitrary criteria*** (e.g. applying optics-based criteria in judgment of spatial resolution of the PAM technique), and in an ***ad hoc manner*** (e.g. analysing a set of beamform maps for various frequency bands, and attempting to draw a concerted conclusion on them).

The present project has been aimed at developing an objectivized, algorithmized procedure for simultaneous evaluation of PAM results on axial fans in various frequency bins, in order to localize and identify the significant broadband noise sources radiating toward the fan suction side.

The procedure can be exploited in studying the purposefulness and effectiveness of technical solutions for drastically reducing e.g. the noise related to the blade tip region, such as reduction of tip leakage noise and / or double leakage noise.

1.4. Extension of the 2D fan design database

The technical literature includes aerodynamic data on 2D basic models of axial fan blade sections, i.e. lift and drag coefficients at various angles of attack. Such data serves as a basis for preliminary design of axial flow blade cascades in a 2D view, i.e. by spanwise segment splitting of the blading.

Aerodynamic data on blade profiles used in classic low-speed fan design, i.e. traditional airfoils and circular-arc cambered plates, are available in the Reynolds number o.m. $\geq 10^5$. No spatially resolved acoustic data are available on the self-noise of low-speed blade sections used in traditional low-speed fan design.

The present project has been aimed at extending the available 2D fan design database with aerodynamic data on traditional isolated blade profiles (airfoil, circular-arc cambered plate) for o.m. of Re = $10^4 \div 10^5$. The aerodynamic effects of blade manufacturing simplifications, frequently used for low-speed fans (e.g. circular-arc plate blades, leading and trailing edges left blunt after laser cutting), were aimed to be investigated. An experimental methodology was intended to be developed for spatially resolved measurements on the aerodynamic self-noise of such profiles.

By means of the extended database, both aerodynamically and aeroacoustically feasible low-speed fan blade sections can be designed. The aerodynamically and aeroacoustically reasonable manufacturing simplifications give a potential for cost-effective blade manufacturing, thus improving the competitivity of the product on the market.

2. PROJECT ACTIVITIES

2.1. Extension of semi-empirical modelling of noise emission of realistic low-speed fan rotors

The following preliminary research phases were carried out for establishing a firm background for this sub-project.

- In [1], the practical (industrial) aspects of fan noise reduction were discussed in detail, and the advanced capabilities of the PAM technique were overviewed.
- In [5], it has been pointed out that the broadband aeroacoustic sources of the case study fan can clearly be separated from solid mechanics noise sources (e.g. blade vibration).
- In [7], preliminary on-site PAM studies were taken on an industrial jet fan, in order to gather experience on industrial PAM applications.
- In [8], attention has been drawn to the fact that the non-radial blade stacking fashion and the controlled vortex design style, characterising the case study fan used in the sub-project, has a remarkable impact on both aerodynamics and aeroacoustics via the tip leakage flow.
- In [4][7][11], studies were carried out on the details of PAM evaluation, with special regard to the practically relevant definition of spatial resolution; evaluation of noise peaks; and impact of duct modes (if relevant).
- For preparation of the future aeroacoustic investigation of realistic ducted fan configurations, the new concept of the "acoustically transparent duct" has been established and tested in a simplified case study [21].

The activity reported herein is focussed on PAM measurements on the noise radiated upstream of an unducted case study fan, equipped with a short-tapered (**SH**) inlet. In the Workplan, PAM measurements on the downstream-radiated sound were also targeted. The PAM-based diagnostics method was further developed and supplemented for downstream measurements. Auxiliary measurements were taken from the downstream direction [2]. As these initial measurement experiences showed, downstream PAM measurements caused the risk of PAM microphone overloading. Against this, the PAM equipment was compelled to be placed at a larger distance from the fan. However, this led to a critical deterioration in the spatial resolution of the technique. Therefore, the continuation of downstream PAM measurements was decided to be terminated.

The PAM-based diagnostics method was further developed for a more effective exploration of phenomena related to the tip leakage flow [2][9]. Source ambiguity problems occurring in evaluating the source maps, related to blade-passage periodicity of the sources, have been solved. To this end, the experimental hardware was further developed (extension with a local leakage flow-reducing appendage). The source maps have been evaluated in detail. On this basis, the concept of double-leakage flow noise has been introduced. The following noise sources have been identified: tip leakage flow noise – also incorporating double-leakage flow noise –; blade trailing edge noise. The latter has been found to be clearly separated from the tip leakage flow noise.

For the trailing edge noise, the evaluation method has been further developed, on the basis of the measurement results and the semi-empirical 2D blade cascade considerations. The wake momentum thickness was eventually taken as a loss indicator, considered as an input to the BPM model (see Section 1.1). The methodological development has been published in [2-3][9].

Refined 3D Computational Fluid Dynamics (**CFD**) simulation tools were elaborated, experimentally validated, and applied, in order to discover the flow phenomena in the inlet section, within the rotor blade passages and in the blow-out zone [3]. The CFD modelling methodology provided a basis for Computational Aero-Acoustics (**CAA**) modelling as well.

In a later phase [25], the noise for various rotor speeds was tested using PAM and a novel evaluation technique – accounting for the limited PAM spatial resolution along the blade span –, in order to check the validity of the acoustic scaling laws over a wide Reynolds number range. The spatially resolved, uniquely processed acoustic measurement data, obtained for the rotating elemental cascades, were compared to the BPM model. The fair agreement revealed that the applicability of the BPM model can be expanded to realistic rotating cascades over parametric ranges (e.g. Reynolds number, blade solidity etc.) being wider than the ranges already published in the literature.

On the aforementioned basis, with appropriate modifications, the applicability of the BPM model for predicting the trailing edge noise has been extended to annular cascades of unducted low-speed fan rotors, consisting of circular arc-cambered plate blades, for Re = $2.3 \cdot 10^4 \div 2 \cdot 10^5$, over wide ranges of cascade geometrical and flow parameters. The extended model agrees well with the experimental data over a noise level range of 40 dB, with a discrepancy of less than ± 3 dB for 90 % of the cases investigated.

These results have been documented in the PhD Thesis [25]. In the thesis point related to these results in [25], the publications [2-3][5][8-9], supported by the NKFI project, are referred to as a basis. The results form the basis of a WoS journal paper to be submitted in the future (under preparation).

2.2. Study on noise-reducing appendages

As far as noise-reducing appendages are concerned, the Workplan originally aimed at testing short inlet ducts and rotor blade tip endplates. As the initial experiments showed [2], the primary tip leakage flow as well as „double leakage" – i.e. when the leakage flow originating from a given tip clearance reaches the adjacent blade tip and leaks across again – plays a major role in noise emission. Therefore, it was intended to *retain the possibility* of development of tip leakage flow in the ongoing studies – i.e. *not to fully prevent* its formation by means of a blade tip endplate –, and to study noise-reducing appendages *influencing* the tip leakage flow presumably in a favourable manner. Such intention has led to the choice of quarter-circle inlet bellmouths of various geometries – being anyway of great practical relevance – as subjects of the studies, instead of rotor blade tip endplates.

The experiences gathered using the PAM technique as described in Section 2.1 have been supplemented with measurements using a handy sound pressure level meter. The unducted configuration, equipped with a SH inlet, has been measured from the upstream direction. Then, the fan has been equipped with a short duct + quarter-circle inlet bellmouth (**BM**), and the measurements were repeated. Such modification resulted in a noise reduction of 5 dB(A) [10]. Such global trend of noise reduction, pointed out by means of a sound pressure meter, has been compared to the PAM results. On this basis, a comprehensive survey has been carried out on the physical background of noise reduction [10]. It was found that the noise reduction caused by the BM is mainly due to the suppression of the peripheral zone of inlet flow separation, and thus, elimination of the double-leakage flow and the related noise.

In a later phase [25], the experimental facility has been further developed. Three versions of short duct + inlet BM have been manufactured. The rounding radii of the three bellmouths were 5 %, 17 %, and 25 % of the duct diameter. The acoustic effect of the various noise-reducing configurations (bellmouths with various radii) has been investigated from the upstream direction. The results have been compared to the PAM results for the SH inlet configuration. The assemblies were tested for various rotor speeds. The acoustic measurements were supplemented with CFD investigation, with special regard to the Reynolds number-dependent and inlet geometry-dependent tip leakage flow and its acoustic impact.

On this basis, experimentally established guidelines have been formulated for the noise-reducing mechanism of a quarter-circle bellmouth entry inlet, and for its design. It was found that the bellmouths with rounding radii of 17 % 25 % of the duct diameter – the latter proposed in ISO 5801:2017 – cause a sound power level reduction of 5 ÷ 6 dB.

These results have been documented in the PhD Thesis [25]. In the thesis point related to these results in [25], the publication [10], supported by the NKFI project, is referred to as a basis. The results form the basis of a WoS journal paper to be submitted in the future (under preparation).

2.3. Objectivization and algorithmization of the PAM evaluation procedure

The noise pattern in the near-tip region of the fan is especially complex. This fact initiated the elaboration of an algorithmized method for localization / evaluation of the noise sources, associated with distinct aerodynamic phenomena. The noise patterns obtained in sub-project described in Section 2.1 were taken as samples. In a preliminary phase, the noise pattern has been subjected to a Fourier analysis, enabling the filtration of the data [13]. In a next phase, retaining the benefits of Fourier filtration, a fuzzy c-means clustering technique has been developed for localizing the individual noise sources associated with physically distinct flow phenomena [12]. By such means, blade-passage-periodic noise sources can be identified and quantified, simultaneously over multiple frequency bands. In application of the evaluation method, the arbitrary and subjective elements can be minimized. To the best knowledge of the research team, this methodology is the first one in which fuzzy c-means clustering is applied to fan rotor beamforming results.

The evaluation procedure, supported with a thorough aeroacoustics evaluation and interpretation of the results obtained near the blade tip radius, has been published in [22]. The fuzzy c-means clustering technique has been extended to periodic datasets, enabling the consideration of blade-passage-periodic noise patterns in clustering. Such further development of the technique, supported with evaluation case studies along the entire blade span, has been published in [28].

Therefore, an objectivized, algorithmized procedure has been developed for simultaneous evaluation of PAM results on axial fans in various frequency bins, at selected rotor radii, in order to localize and identify the significant blade-passage-periodic broadband noise sources radiating toward the fan suction side. The procedure is based on Fourier filtration, and blade-passage-periodic fuzzy c-means clustering.

As an outlook of this sub-project, preliminary studies were carried out on the further development possibilities of the beamforming technique applied to axial flow rotors, from the aspects of experimental hardware, data acquisition, and data processing [26-27].

2.4. Extension of the 2D fan design database

The following preliminary studies were carried out within this sub-project.

- In [6], the fluid dynamics of blade boundary layers exposed to a significant adverse pressure gradient, leading to boundary layer thickening (or even separation) have analytically been studied, for a more comprehensive understanding of phenomena on the blade suction side downstream of the suction peak.
- In [16-19], preliminary studies were carried out on vortex shedding phenomena, being the origin of profile vortex shedding noise as a dominant source in low-speed axial fans. The following aspects were considered: establishment of high-fidelity CFD simulation methodology for vortex shedding; establishing a basis also for CAA techniques.

Within this sub-project, wind tunnel experiments, involving the PAM technique and its special evaluation, have been carried out for establishing a beamforming dataset on the self-noise (e.g. profile vortex shedding noise) generated by basic 2D models of low-speed axial fan blade sections, such as a flat plate, a cambered plate, and a RAF6-E airfoil, for moderate chord Reynolds numbers ($Re = 6\cdot10^4 \div 1.4\cdot10^5$), over wide ranges of angles of attack [14-15][23]. Special emphasis is given to development of profile vortex shedding noise at moderate Reynolds numbers. In [20], a basic CFD methodology has been developed for aerodynamic investigation of blade sections, as supplementary information to the wind tunnel measurements.

In [24], the literature database has been extended by aerodynamic measurements (lift, drag, lift-to-drag ratio) on the basic models of blade sections. At Reynolds numbers below the o.m. of 10^5, the circular arc cambered plate blading was found to be aerodynamically more favourable than the profiled one. This gives a potential for realization of high-efficiency low-speed fans of cost-effective manufacturing. The effect of blunt leading edge has been studied at various flow conditions.

On the aforementioned basis, the 2D fan design database has been extended for consideration of easy-to-manufacture blade geometries in fan design in the low Reynolds number range, enabling good efficiency and moderate noise.

The acoustic studies form the basis of a future publication is a WoS journal (under preparation).

3. PUBLICATIONS; INVOLVEMENT OF YOUNG RESEARCHERS; EDUCATION OF TALENTED STUDENTS

In the Workplan, the following publication activity was undertaken for the entire project:

- 4 journal papers in Hungarian
- 7 international conference papers
- 4 international journal papers

The publication activity has been realized as follows:

- 3 journal papers in Hungarian [1][16-17]
- 11 international conference papers [2-4][6-7][10-12][15][23][27], including: *European Conference on Turbomachinery Fluid Dynamics and Thermodynamics / Conference on Modelling Fluid Flow / International Conference on Fan Noise, Technology and Numerical Methods / ASME Turbo Expo: Turbomachinery Technical Conference and Exposition / Berlin Beamforming Conference*
- 5 WoS journal papers (with Impact Factor): [8-9][22][24][28], including: *Journal of Sound and Vibration* – Q1, IF (2017): 2,618, IF (2016): 2.593 / *Proc. IMechE, Part A - Journal of Power and Energy* – Q3, IF (2017): 1.022, IF (2014): 0.645 / *International Journal of Aeroacoustics* – Q4, IF (2015): 0,414

- 1 PhD thesis [25]
- 5 journal papers, without Impact Factor, written in English [5][13-14][18][26]
- 3 conference papers in Hungarian [19-21]

The project contributed to the doctoral programmes of 3 PhD students / PhD candidates (BENEDEK Tamás, TÓTH Bence Mihály, BALLA Esztella Éva). Apart from them, 11 talented engineering students have been involved in the sub-projects.

4. REALIZED AND ENVISAGED PRACTICAL UTILIZATION OF PROJECT RESULTS: AN OUTLOOK

The following activities have been carried out in collaboration with industrial firms. The names of the firms and further details of the projects have been left non-disclosed in the present report, for confidentiality reasons.

- Elaboration of a simplified (based on the VDI 3731 technical guideline) semi-empirical preliminary design and checking method for industrial axial fans, aiming at a sound power level reduction of approx. 6 d*B* at prescribed aerodynamic performance. Proposal for elaborating an improved, refined semi-empirical methodology for blade self-noise prediction, on the basis of the final results of the ***sub-project described in Section 2.1***.

- Diagnostics on the vibrational behaviour of a 1600 *mm*-diameter axial fan, on the basis of noise samples obtained next to the outlet air jet as well as by plucking the blades, considering the experiences on blade profile vortex shedding noise obtained in the ***sub-project described in Section 2.4***. Proposal for modifying the fan construction for life cycle improvement.
- Development of a new industrial fan family in the 250 *mm* - 2000 *mm* rotor diameter range, considering noise reduction in design. In design of the rotor inlet cones, consideration of experiences of ***sub-project described in Section 2.2***. Phased array measurements on the prototype fan. In evaluation of the results, consideration of experiences of ***sub-project described in Section 2.3***. (project in progress)

5. PUBLICATIONS ELABORATED WITHIN THE FRAMEWORK OF THE PROJECT

[1] Tóth B, Vad J, 2014, Ipari axiális ventilátorok akusztikai diagnosztikája, *Magyar Épületgépészet*, **LXIII** (11), pp. 18-20, ISSN: 1215-9913 (Acoustics diagnostics of industrial fans) (in Hungarian)

[2] Benedek T, Vad J, 2015, Spatially resolved acoustic and aerodynamic studies upstream and downstream of an industrial axial fan with involvement of the phased array microphone technique, *ETC'11 - The 11th European Conference on Turbomachinery Fluid Dynamics and Thermodynamics*, Madrid, Spain, 23-27 March 2015, Paper # 128, 11p, ISSN: 2410-4833

[3] Benedek T, Vad J, 2015, Case-specific semi-empirical guidelines for simultaneous reduction of loss and emitted noise in an axial flow fan, *CMFF'15 - Conference on Modelling Fluid Flow*, Budapest, Hungary, 1-4 September 2015, Paper # 108, 8p, ISBN: 978-963-313-190-9

[4] Horváth Cs, Tóth B, Tóth P, Benedek T, Vad J, 2015, Reevaluating noise sources appearing on the axis for beamform maps of rotating sources, *Fan 2015 - International Conference on Fan Noise, Technology and Numerical Methods*, Lyon, France, 15-17 April 2015, Paper # 13, 11 p, ISBN: 978-0-9572374-3-8

[5] Kalmár-Nagy T, Bak B D, Benedek T, Vad J, 2015, Vibration and noise of an axial flow fan, *Periodica Polytechnika, Mechanical Engineering*, **59** (3), pp. 109-113, ISSN: 1587-379X

[6] Lukács E, Vad J, 2015, On the track of the Borda-Carnot loss, *CMFF'15 - Conference on Modelling Fluid Flow*, Budapest, Hungary, 1-4 September 2015, Paper # 78, 6p, ISBN: 978-963-313-190-9

[7] Tóth B, Vad J, 2015, Challenges in evaluating beamforming measurements on an industrial jet fan, *CMFF'15 - Conference on Modelling Fluid Flow*, Budapest, Hungary, 1-4 September 2015, Paper # 186, 5p, ISBN: 978-963-313-190-9

[8] Vad J, Halász G, Benedek T, 2015, Efficiency gain of low-speed axial flow rotors due to forward sweep, *Proc. IMechE, Part A - Journal of Power and Energy*, **229** (1), pp. 16-23, ISSN: 0957-6509

[9] Benedek T, Vad J, 2016, An industrial on-site methodology for combined acoustic-aerodynamic diagnostics of axial fans, involving the Phased Array Microphone technique, *International Journal of Aeroacoustics* – Special Issue on Turbomachinery Aeroacoustics, **15** (1-2), pp. 81-102

[10] Benedek T, Vad J, 2016, Study on the effect of inlet geometry on the noise of an axial fan, with involvement of the phased array microphone technique, *Proceedings of ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition GT2016*, Paper ID GT2016-57772, 13-17 June 2016, Seoul, South Korea

[11] Horváth Cs, Tóth B, 2016, Separating apart the contributions from multiple tonal noise sources which are localized to the Mach radius, *Berlin Beamforming Conference (BeBeC)*, Paper ID BeBeC-2016-D16, Berlin-Adlershof, Germany, 29 February - 01 March 2016

[12] Tóth B, Vad J, 2016, An efficient methodology for comprehensive evaluation of turbomachinery source maps, *Berlin Beamforming Conference (BeBeC)*, Paper ID BeBeC-2016-D17, Berlin-Adlershof, Germany, 29 February - 01 March 2016

[13] Tóth B, Vad J, 2016, Fourier analysis of beamforming data at the tip of an axial fan rotor, *Periodica Polytechnika, Mechanical Engineering*, **60** (3), pp. 152-158, ISSN: 1587-379X

[14] Balla E, Vad J, 2017, Establishment of a beamforming dataset on basic models of low-speed axial fan blade sections, *Periodica Polytechnika, Mechanical Engineering*, **61** (2), pp. 122-129, ISSN: 1587-379X

[15] Balla E, Vad J, 2017, Beamforming studies on basic models of low-speed axial fan blade sections, *ETC'12 - The 12th European Conference on Turbomachinery Fluid Dynamics and Thermodynamics*, Stockholm, Sweden, 3-7 April 2017, Paper # 119, 12p

[16] Fenyvesi B, 2017, Vortex áramlásmérő kalibrálási tapasztalatai, *GÉP*, **LXVIII** (1), pp. 45-51, ISSN: 0016-8572 (Calibration experiences of a vortex flowmeter) (in Hungarian)

[17] Fenyvesi B, 2017, Vortex áramlásmérõk rendhagyó nemlinearitás-vizsgálata, *Magyar Épületgépészet*, **LXVI** (5), pp. 25-28, ISSN: 1215-9913 (Uncommon investigation on the non-linearity of vortex flowmeters) (in Hungarian)

[18] Fenyvesi B, Horváth Cs, 2017, Investigation on the nonconstant behavior of a vortex flow meter with narrow gauge pipe via conducting measurements and numerical simulations, *Periodica Polytechnika, Mechanical Engineering*, **61** (3), pp. 247-254, ISSN: 1587-379X

[19] Fenyvesi, B, 2017, Vortex áramlásmérő nemlineáris viselkedésének vizsgálata numerikus szimuláció alkalmazásával, *XXV. Nemzetközi Gépész Találkozó (OGÉT)*, Kolozsvár, Románia, 2017. április 27-30, pp. 139-142 (Investigation on the nonlinear behaviour of a vortex flowmeter by means of computational fluid dynamics) (in Hungarian)

[20] Nagy B, Balla E, 2017, Szárnymetszetek körüli áramlás szimulációja alacsony Reynolds-számokon, *Tavaszi Szél 2017 Konferencia*, Miskolc, Magyarország, 2017.03.31-2017.04.02, pp. 90-101, ISBN:978-615-5586-18-7 (Simulation on the flow past airfoil sections at low Reynolds numbers) (in Hungarian)

[21] Tokaji K, Horváth Cs, 2017, Akusztikailag átlátszó cső tervezése, *XXV. Nemzetközi Gépész Találkozó (OGÉT)*, Kolozsvár, Románia, 2017. április 27-30, pp. 416-419 (Design of an acoustically transparent duct) (in Hungarian)

[22] Tóth B, Vad J, 2017, Algorithmic localisation of noise sources in the tip region of a low-speed axial flow fan, *Journal of Sound and Vibration*, **393**, pp. 425-441, ISSN: 0022-460X

[23] Balla E, Vad J, 2018, Combined aerodynamic and phased array microphone studies on basic models of low-speed axial fan blade sections, *Proceedings of the ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition GT2018*, Paper ID GT2018-75778, 11-15 June 2018, Lillestrom, Norway

[24] Balla E, Vad J, 2018, Lift and drag force measurements on basic models of low-speed axial fan blade sections, *Proc. IMechE, Part A - Journal of Power and Energy*, Online first, 11p, ISSN: 0957-6509

[25] Benedek T, 2018, Axiális átömlésű ventilátor mikrofontömbös diagnosztikája, Budapesti Műszaki és Gazdaságtudományi Egyetem Doktori Iskola: Pattantyús-Ábrahám Géza Gépészeti Doktori Iskola. Tudományág: műszaki tudományok/gépészeti tudományok (Phased array microphone diagnostics on an axial flow fan) (*PhD Thesis*) (in Hungarian)

[26] Kotán G, Tóth B, Vad J, 2018, Comparison of the rotating source identifier and the virtual rotating array method, *Periodica Polytechnica, Mechanical Engineering*, **62** (4), pp. 261-268, ISSN: 1587-379X

[27] Tóth B, Kalmár-Nagy T, Vad J, 2018, Rotating beamforming with uneven microphone placements, *7th Berlin Beamforming Conference (BeBeC)*, Paper ID BeBeC-2018-D23, Berlin-Adlershof, Germany, 5-6 March 2018

[28] Tóth B, Vad J, 2018, A fuzzy clustering method for periodic data, applied for processing turbomachinery beamforming maps, *Journal of Sound and Vibration*, **434**, pp. 298-313, ISSN 0022-460X