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A Review of the Fan 2015 International Conference on Fan Noise, Technology and Numerical Methods



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ABSTRACT

In 2015 the Institution of Mechanical Engineers (IMechE), Centre Technique des Industries Mécaniques (Cetim) and Centre Technique des Industries Aérauliques et Thermiques (Cetiat) organised a conference focused on fans intended for air movement application. The resulting conference, Fan 2015, took place in Lyon, France between April 15th and 17th 2015, http://www.fan2015.org. This AMCA International white paper presents a review of the papers presented at the Fan 2015 conference. AMCA International policy is to publish white papers on issues of importance to the air movement and control industry, and to do so at no cost for the benefit of the industry.

The review identifies three broad themes that are of primary importance to the air movement fan community:

- compliance with both current and forthcoming regulatory requirements mandating minimum allowable fan or fan and motor efficiency levels;
- the practical problems associated with application of numerical methods into air movement fan design and development processes;
- the challenge presented by the prediction of fan tonal and broadband noise.

The linkage between papers presented at the conference and the three themes is discussed, clarifying the overarching drivers of action today within the air movement community. The paper concludes with a summary of the actions those working within the air movement fan community are addressing now and continue to regard as a priority. In so doing the paper clarifies the collective contribution to knowledge of the presented papers, current priorities within the air movement community and the drivers of those priorities.

Keywords: fan noise, fan technology, numerical methods.

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1.0 INTRODUCTION AND METHODOLOGY

As observed by Corsini *et al.* (2013), within the European Union (EU), Commission Regulation No. 327/2011 became legally binding on 1 January 2013, setting minimum Fan and Motor Efficiency Grades (FMEGs) for air movement fans (Commission Regulation (EU) No. 327/2011). For applicable fans the 2013 minimum fan and motor efficiency grades have resulted in approximately 33 per cent of those fans sold before 1 January 2013 now illegal within Europe (Hauer and Brooks, 2012). These minimum fan and motor efficiency grades became more stringent on 1 January 2015 resulting in a proportion of those fans sold before 1 January 2015 also now illegal within Europe. Moreover, these minimum fan and motor efficiency grades will become more stringent again on 1 January 2020.

Corsini *et al.* (2013) went on to observe that in the USA, the US Department of Energy monitors regulatory activity within the European Union. On 1 February 2013, the US federal government published a framework document in the Federal Register, outlining the approach to fan efficiency regulation within the USA (US Department of Energy, 2013). The framework reflected a desire to be consistent with many elements of the European approach in EU Commission Regulation No. 327/2011 (US Department of Energy, 2013). The Department of Energy rule-making process will be completed by the end of 2015, with the intent of regulating minimum fan efficiencies within the USA by 2020.

Given today's regulatory environment we may conclude that in all global regions, minimum fan or fan and motors efficiencies will become mandatory and then increase over time. As a direct result, pressure on the air movement fan community will increase to both develop fans with high peak efficiency, and also specify them such that they operate closer to their peak efficiency point when installed.

In response to the changing regulatory environment the Institution of Mechanical Engineers (IMechE), Centre Technique des Industries Mécaniques (Cetim) and Centre Technique des Industries Aérauliques et Thermiques (Cetiat) identified a need for an air movement fan conference, Fan 2015 held in Lyon, France from April 15 to 17 2015. The primary function of a technical conference is to provide a forum for a community to present current research. In essence a conference clarifies what research a community is engaged in and therefore what that community collectively considers important.

However, a technical conference comprises a collection of technical papers written in isolation. A review of the papers presented at the Fan 2015 conference therefore has the potential to make both a general and specific contribution. It may make a general contribution by summarising the conferences collective contribution to knowledge. It may make a specific contribution by providing an insight into how the air movement community has responded to recently introduced regulation, and is responding to forthcoming regulation.

The author recognised the value of providing a post-conference review clarifying both the identified general and specific contributions. To facilitate this review the author chose to adopt an ethnographic methodology while organising the conference. We may characterise analytical research strategies as the generation of data followed by its analysis. In contrast, an ethnographic methodology has at its core the concept of 'theory from data' which is the process by which theory emerges from data as free as possible from preconceived values and models that the researcher imposes (Denzin and Lincoln, 2003).

The conference organising committee issued a general call for papers, placing no limit on the topics conference papers could address, with one exception. Papers must address research conducted on air movement fans; research conducted on fans intended for aerospace applications were specifically excluded from the scope of the conference. The submitted abstracts were reviewed by members of the conference organising committee who determined that they related to one of three themes:

1. the application of computational methods to fan design;
2. fan technology; and,
3. fan noise.

Members of the conference organising committee reviewed the papers attributed to the first theme and identified that a common topic was the need to improve fan efficiency in response to current and forthcoming regulatory

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requirements. They reviewed the papers attributed to the second theme and identified that a common topic was the need to improve the fan design process to avoid in-service failures. They reviewed the papers attributed to the third theme and identified that a common topic was the need to improve the accuracy with which fan noise was predicted. In response the author invited three key-note speakers to give lectures at the conference:

- Marcos Gonzalez Álvarez, Policy Officer, European Commission — Directorate General for Energy gave the key-note lecture "Ecodesign Requirements on Fans: Current Situation and Future Developments" (Gonzalez Álvarez, 2015).
- Alain Godichon, President – AG Consulting gave a key-note lecture "Fan Design, Past, Present and Future" (Godichon, 2015).
- Stephane Moreau, University of Sherbrooke, Canada gave a key-note lecture "Numerical and Analytical Predictions of Low-Speed Fan Aero-Acoustics" (Moreau, 2015).

During the paper review process members of the conference organising committee identified sub-themes within each of the three identified conference themes. These sub-themes were used as the titles of each session within the conference. In this review paper the conference structure is retained. A summary of each key-note lecture is presented in Section 2. Each paper presented in the application of computational methods to fan design track is reviewed in Section 3. Each paper presented in the fan technology track is reviewed in Section 4. Each paper presented in the fan noise track is reviewed in Section 5. In Section 3, 4 and 5 each sub-section headings follows the conference session titles. In each sub-section the papers are reviewed in the order they were presented.

During the conference the author drafted a one-paragraph summary of each paper as it was presented. Immediately following each session a one-paragraph summary of the session was drafted. Sections 3, 4 and 5 each include sub-sections containing the reviews of each paper, plus a final sub-section comprising the reviews of each conference session. In Section 6 these reviews plus summaries of each key-note lecture are used as input to a discussion, identifying current issues facing the air movement fan community. From this analysis common themes emerged that enabled the author to identify:

- the conferences collective contribution to knowledge;
- how the air movement community has responded to recently introduced regulation; and,
- what the air movement fan community is doing now in response to forthcoming regulation.

The paper ends with a summary of the most important issues facing the air movement fan community today and the action those working both within and with the community are taking in response.

2.0 CONFERENCE KEY-NOTE LECTURES

In his key-note lecture Mr Gonzalez Álvarez presented an overview of European Union policies relating to energy efficiency, and specifically the energy efficiency of products including fans for air movement applications. The key-note lecture focused on European Commission Regulation 327 that became legally binding within the European Union on January 1st 2013. This Directive sets minimum allowable efficiency levels for air movement fans and motors, with manufactures being required to label their products with its Fan and Motor Efficiency Grade (FMEG). Although difficult to predict accurately, those working within the air movement fan community estimate that between 33% and 50% of the products being sold in 2012 did not comply with the minimum FMEG levels that became legally binding on January 1st 2013. The minimum FMEG levels were increased again on the 1st January 2015, eliminating additional low efficiency fans from the European market. Mr Gonzalez Álvarez confirmed that he is currently managing a review of Regulation 327. By the end of 2015 he expects to have finalised recommendations for amending Regulation 327 and increasing minimum FMEG's. The amended version of Regulation 327 and the higher minimum FMEG's that will come into effect on January 1st 2020.

In his key-note lecture Mr Godichon presented an overview of the evolution of the fan industry over the last five decades. In the 1960's the primary challenges facing the air movement fan community were the accurate prediction of fan performance and the prediction of fan noise. However, the most acute challenge was the technical reliability

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of fan mechanical designs. In-service failures were regrettably common. These failures were primarily as a consequence of the design methods used. Stress calculations were made manually, with limited ability to model boundary conditions. Design engineers relied on the use of experimental measurements made using strain gauges but these gave measurements at the strain gauge location only. Brittle lacquer was used to give a qualitative assessment of the stress over the entire impeller; however the technique was sensitive to temperature and could not give an accurate assessment of peak stress levels. It was only the emergence of finite element analysis in the early 1970's that provided design engineers with the insight needed to avoid in-service mechanical failure. By the year 2000 design engineers were starting to use computational fluid dynamics codes to predict fan performance. Despite the limitations of available computer hardware and the computational fluid dynamics codes running on them the results could be accurate enough to be useful if the computational mesh was well conditioned and boundary conditions were well specified. The years from 2000 to 2010 were characterised by the increasing use of numerical methods to predict both fan performance and to provide insight into the blade-to-blade flow-field physics.

During the 1960's the prediction of fan noise was based exclusively on model tests followed by the use of empirical methods to scale model to full size fan noise. The first theoretical acoustic methods were developed in the early 1970's providing a characterisation of the aero-acoustic physics. These methods have been progressively incorporated into computational fluid dynamics codes, and at the time of writing it is possible to predict fan spectrum and broadband noise. However, the computational effort required is high and remains beyond that available within the air movement fan community. Rather than focusing on the prediction of fan noise, design engineers are increasingly focusing on the use of computational methods to automate the fan design process. In so doing it becomes possible to tailor fan designs to the required duty point, maximising efficiency whilst also minimising fan size and therefore manufacturing costs. The primary advances in fan technology over the last five decades may be primarily attributed to the increasing use of numerical methods. The application of numerical methods to mechanical design has resulted in in-service mechanical failures being largely eliminated. The application of numerical methods is currently focused on predicting fan aerodynamic performance. In the future the availability of higher-power computing clusters will result in the increasing use of computations methods to predict fan spectrum and broadband noise.

In his key-note lecture Professor Moreau presented an overview of the application of numerical methods to the aero-acoustic analysis of air movement fans. A key challenge facing design engineers when attempting to predict fan noise is that the flow though an air movement fan is transitional. Consequently the flow-field is characterised by turbulence that is classically difficult to predict. Analytical methods for predicting fan noise are invariably based on a series of simplifying assumptions. Despite this caveat analytical methods can be used to model the unsteady pressure generated by near-field noise sources that can then be related to fan far-field noise. The primary noise sources associated with an air movement fan originate in the boundary layer and blade tip-to-casing flow. These are then augmented by noise sources associated with other turbulent structures that develop through the blade-to-blade passage or upstream of the fan.

Blade trailing edge noise originates as a consequence of the unsteady pressure in the blade trailing edge region. The unsteady pressure radiates to the far-field as broadband noise. When modelling fan noise each blade is considered as an isolated rotating aerofoil, with each being treated as an individual noise source. These individual rotating noise sources then collectively propagate to the far-field and collectively result in what is perceive in the stationary far-field as broadband fan noise. The practicality of predicting the unsteady pressures associated with near-field noise sources requires the use of a large eddy simulation of the flow-field. The formidable computational effort associated with the use of large eddy simulations is simply beyond that available to design engineers working within the air movement fan community. Consequently the use of Reynolds-Averaged Navier-Stokes (RANS) simulations of the flow-field provides a way to predict fan broadband noise in combination with a series of modelling assumptions. These assumptions provide a way to account for the flow-field physics not inherently modelled by a RANS simulation of the flow-field. In contrast Direct Numerical Simulations (DNS's) are becoming possible as a consequence of the increasing availability of high performance computing clusters. Although requiring approximately 1000 times the computing power typically available within the air movement community, academics are starting to undertake DNS's. These simulations model the flow-field directly, avoiding the needs for modelling assumptions and therefore avoiding the errors inherent in their use. At the time of writing DNS's are used on at least a semi-routine basis to predict isolated aerofoil noise. However, they are only exceptionally applied to the prediction of fan noise as a consequence of the computational effort required.

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3.0 THE APPLICATION OF COMPUTATIONAL METHODS TO FAN DESIGN

The application of computational methods to air movement fan design has been driven over the last five years by current and forthcoming regulation within both the European Community and the USA, Sheard (2015). This regulation mandates minimum allowable fan efficiency levels that fan designers must achieve if they are to legally place their product on the market. There is consequently increasing interest within the air movement fan community in design methods that may be utilised to improve fan efficiency. Those researchers developing design methods have focused their effort into four areas of endeavour:

- optimisation methods for axial fans;
- theoretical design methods for axial fans;
- numerical methods for axial and mixed flow fans; and,
- theoretical and numerical methods for centrifugal fans.

3.1 OPTIMISATION METHODS FOR AXIAL FANS

Bamberger *et al.* (2015b) studied the optimisation of low pressure axial fans. The purpose of the optimisation was to maximise efficiency at a single design point. Manufacturing limitations were modelled as a set of constraints during the optimisation process. The optimisation process utilised a Multi-Layer Perception (MLP) neural network that varied parameters used to define fan geometry. The resulting optimisation process proved to be both quick to use with results that were in good agreement with experimental measurements. The optimisation process is therefore concluded to be suitable for evaluating the viability of design changes intended to increase fan efficiency within pre-determined design constraints.

Heo *et al.* (2015) utilised a fully three-dimensional aerodynamic and aero-acoustic analysis when optimising the design of a low-pressure axial fan. The optimisation process included preliminary design, three-dimensional and aero-acoustic analysis of the resulting fan designs performance. The purpose of the optimisation was to integrate both design and analysis into the optimisation process. The initial fan design was generated using a one-dimensional analytic method and then analysed using a three-dimensional computational fluid dynamics code. The three-dimensional computational domain was automatically generated from the initial design. Results from the three-dimensional aerodynamic and aero-acoustic analysis were then used as input to either a single or multi-objective optimiser. The output from the optimiser was then used to adapt the initial design geometry prior to re-analysis. The optimisation method provides fan designers with a way to optimise both fan aerodynamic and acoustic performance.

Lorcher (2015) developed a computational fluid dynamics code for optimising the design of an axial fan that formed part of a heat pump condensing system. This optimisation process aimed to optimise heat pump condensing system performance as opposed to fan performance. The optimisation focused on a typical heat pump condensing system at four operating points that varied as a consequence of changing climatic condition over a one-year operating cycle. The purpose of the optimisation was to minimise heat pump condensing system energy consumption over a one-year operating cycle. A semi-automatic optimisation process was used to optimise fan geometry, with a computational fluid dynamic analysis of the heat pump condensing system then being used to provide feedback that was then used to modify fan geometry. The optimisation process was able to generate new fan geometry that when built and installed resulted in a 30 percent reduction of annual energy consumption compared to a non-optimised fan.

3.2 THEORETICAL DESIGN METHODS FOR AXIAL FANS

Heinrich *et al.* (2015) conducted an experimental and numerical investigation of a gearless one-motor contra-rotating fan. Traditionally counter-rotating fans have been used in applications requiring a higher pressure duty point then can be achieved in a single stage fan. Two fan, rotating in opposite directions for the counter-rotating fan. The research reported in this paper presents a single motor concept with one shaft driving both fan impellers. The motors internal rotor is connected to one fan stage and the external rotor of the motor is connected to the other. Performance of the new contra-rotating fan concept was both measured experimentally and predicted using a multiple reference frame approach. Fan efficiency was shown to be higher than a single-stage fan with guide vanes. The authors attributed this increase in efficiency to the novel concept that inherently results in motor torque being evenly distributed between the two impellers.

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Augustyn *et al.* (2015) conducted a numerical and experimental investigation into the accuracy of the fan scaling laws when applied to large diameter axial flow fans. The axial fans applied in air-cooled steam condenser applications are typically ten meters in diameter. Fan performance is typically established by testing a 1.25 meter model of the fan, and then using the fan laws to scale model performance to full size fan performance. However, the difference between model and full size fan diameter is large enough for Reynolds number effects to be potentially significant, degrading accuracy of the resulting prediction of full size fan performance. In this paper the authors measured the performance of a 1.25 meter model of a 10.36 meter fan. They then used both the fan laws and numerical simulation to predict performance of the 10.36 meter fan. The numerical prediction was between two and five percent higher than the scaled performance. The authors attributed this difference to the fan laws not taking Reynolds number effects into account.

Corsini *et al.* (2015a) computed the unsteady coupling between an axial flow fan and the system within which it was embedded using a novel actuator disk and line approach. Fan performance is classically measured in accordance with the international standard ISO 5801 in a standardised airway. In practice air movement fans are typically embedded in a system, resulting is installed fan performance varying significantly from that measured in a standardised airway. In this paper the authors model the fan as a pressure discontinuity. They then go on to present a method for modelling the effect of a gravity damper, with the fan and damper then being embedded within a system. The authors concluded that the resulting system performance was accurately predicted, allowing the optimisation of the relative position of the damper and fan.

Masi *et al.* (2015) studied the use of controlled vortex blading when attempting to increase the efficiency of a rotor-only axial fan. Air movement fans have classically been designed around a free vortex aerodynamic design. Free vortex blades may be cut down and used with a variety of fan and hub diameter combinations. However, blades based on a controlled vortex design can significantly increase a fans pressure developing capability, resulting in the possibility of using a smaller diameter fan for a given duty point. The authors' consider controlled vortex blade loss mechanisms and advocate a design methodology aimed a minimising losses though the blade-to-blade passage. The authors conclude that the resulting design methodology can increase fan efficiency by five percent compared to a classical controlled vortex design methodology.

3.3 NUMERICAL METHODS FOR AXIAL AND MIXED FLOW FANS

Chumakov *et al.* (2015a) evaluated the computational efficiency of a large eddy simulation developed for application with low Mach number axial flow fans. A large eddy simulation can be used to calculate directly the turbulence that characterises the flow-fields inertial sub-range responsible for fan far-field noise. The large eddy formulation developed by the authors utilised an isentropic relationship to couple density and pressure. When solved using a fractional-step method this pressure-density coupling results in a Helmholtz pressure system that implicitly models the near-field origin of fan far-field noise without the need for additional numerical stiffness. The developed method is used to predict the acoustic performance of a fan, and the results compared to measured data. The agreement between predicted and measured fan far-field noise was concluded to be good.

Corsini *et al.* (2015b) conducted an aero-acoustic assessment of the impact of a sinusoidal leading edge on the performance of an axial fan using a hybrid large eddy / Reynolds-averaged Navier-Stoked simulation. The authors developed a hybrid large eddy simulation / Reynolds-averaged Navier-Stokes simulation based on an elliptical relaxation method that they demonstrated to be numerically robust when predicting the blade-to-blade flow-field of a fan intended for air movement application. The authors applied their developed hybrid methodology to predict the acoustic emissions from a fan with a sinusoidal leading edge. They concluded that the sinusoidal leading edge resulted in a re-distribution of blade span-wise acoustic emissions combined with a small overall reduction in fan far-field noise.

Mattern *et al.* (2015) presented a decomposition approach to the modal analysis of blade-to-blade flow-field features. The decomposition approach is compared and contrasted with other available approaches, and the benefits of the advocated approach clarified. The authors argue that this approach provides an efficient method for predicting blade-to-blade flow-field features. Its benefits are demonstrated though a comparison of predicted and measured flow-field parameters within the side-channel of a regenerative pump. Using the approach the authors were able to model the interaction between the channel-side of the pump and the pumps impeller, in so doing providing an insight into the flow-field physics.

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Collison *et al.* (2015) studied the blade trailing edge noise of a mixed flow fan, identifying vortex shedding as the near-field origin of trailing edge induced far-field noise. The authors study the physical mechanisms responsible for far-field noise, and the sensitivity of those mechanisms to changing impeller geometry. The authors' present a design methodology that they use to optimise impeller geometry, minimising far-field noise without reducing fan efficiency. The primary contribution of the methodology is in providing fan designers with a method for predicting the far-field acoustic consequence of trailing edge vortex shedding.

3.4 THEORETICAL AND NUMERICAL METHODS FOR CENTRIFUGAL FANS

Henner *et al.* (2015b) studied the change in fan broadband noise with a change from design to off-design operation. Fans applied into automotive applications are routinely operated at off-design conditions. The authors observed that the change in blade inlet angle associated with off-design operation results in an increase in fan far-field broadband noise. Using a large eddy simulation they were able to identify the presence of vortical structures in the blade trailing edge region. They were then able to identify pressure and density fluctuations within the trailing edge wake that act as a dipolar noise source that correlates with the frequency of trailing edge vortex shedding.

Henner *et al.* (2015a) developed an inverse design method for optimising the geometry of fans intended for automotive application over a range of operating points. Recent attempts to optimise centrifugal fan geometry have had only limited success. Improvement in overall fan performance requires geometry to be optimised for off-design as well as design performance, while respecting manufacturing limitations. In this paper the authors present a computational analysis of an existing centrifugal fan, predicting inlet and outlet air angles onto and off the fan blades. The developed inverse design method was then used to adapt fan geometry, using radial distributions of flow velocity and angle at the blade trailing edge. Fan efficiency was improved as a consequence of a reduction in secondary flow intensity in the volute.

Aldi *et al.* (2015a) developed an optimisation process for application with centrifugal fans incorporating backwards-curved blades. The design procedure for centrifugal fans with backward curved blades is well documented in the literature. These design procedures are classically empirical and are able to predict performance of a fan well when installed in a standardised test system. However, these empirical design procedures are classically less accurate when predicting installed fan performance. The authors' present an optimisation of three centrifugal fan designs using their optimisation process. The resulting optimised fan performance was experimentally verified and demonstrated to have both improved installed and off-design performance.

3.5 CURRENT ISSUES WITH THE APPLICATION OF COMPUTATIONAL METHODS TO FAN DESIGN

The papers focusing on optimisation methods for axial fans collectively illustrate that it is possible to use computational methods to optimise fan performance. The research of Bamberger *et al.* (2015b) illustrates that a relatively simple approach may still result in a useful improvement in fan efficiency. The research of Heo *et al.* (2015) illustrates that it is possible to include acoustic considerations when optimising fan performance. The research of Lorcher (2015) illustrates that system performance as opposed to fan performance may be the subject of optimisation, in so doing maximising system efficiency.

The papers focusing on theoretical design methods for axial fans collectively illustrate that fan efficiency and the efficiency of the system within which a fan is embedded may be improved. The research of Heinrich *et al.* (2015) illustrates that a novel contra-rotating fan concept can operate at a higher pressure then a single stage fan without significantly increasing fan size. The research of Augustyn *et al.* (2015) illustrates that the fan laws may be used to predict the performance of very large fans from relatively small model fan data. The research of Corsini *et al.* (2015a) illustrates that it is possible to optimise both fan and system configuration whilst approximating the fan as a pressure discontinuity in the system. The research of Masi *et al.* (2015) illustrates that there is scope for improving fan efficiency through the use of a novel design methodology for controlled vortex blade design.

The papers focusing on numerical methods for axial and mixed flow fans collectively illustrate numerical methods can provide fan designers with an insight into the acoustic as well as aerodynamic consequence of changes in fan geometry. The research of Chumakov *et al.* (2015a) illustrates that despite the formidable computational requirements, large eddy simulations are now a viable option for designers working within the air movement fan community. The research of Corsini *et al.* (2015b) illustrates that numerical methods may be used to evaluate the acoustic consequences of a change made to a improve fan aerodynamic stability may be quantified

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computationally without the need for a physical prototype. The research of Mattern *et al.* (2015) illustrates that numerical methods may be used to gain an insight into the flow-field physics that would be near impossible using experimental methods alone. The research of Collison *et al.* (2015) illustrates that numerical methods may be used during the fan design process, providing designers with a tool to optimise both fan aerodynamic and acoustic performance.

The papers focusing on theoretical and numerical methods for centrifugal fans collectively illustrate that classical empirical and semi-empirical design methods are able to predict well design point fan performance. However, accurate off-design performance prediction required the use of numerical methods. The research of Henner *et al.* (2015b) illustrates that trailing edge vortex shedding results in a dipolar noise source that may be minimised though an optimisation of blade angles. The research of Henner *et al.* (2015a) illustrates that an inverse design method can be effective when optimising fan design to minimise aerodynamic losses over a range of operating points. The research of Aldi *et al.* (2015a) illustrates that a numerical method can be effective when optimising fan geometry for both off-design and installed performance.

4.0 FAN TECHNOLOGY

The air movement fan community is focused on the development of new fan technology that is primarily driven by an on-going need to comply with a broad range of regulatory requirements. These regulatory requirements impact aerodynamic design, the motors and drives used in a fan system and the wider system within which a fan and its design system are embedded. A desire to avoid in-service mechanical failure is an overarching driver when developing fan technology, Sheard (2014b). There is consequently increasing interest within the air movement fan community in fan technology that may be utilised to facilitate compliance with regulatory requirements while simultaneously minimising in-service mechanical failures. Those researchers developing fan technology have focused their effort into five areas of endeavour:

- measurement and test;
- electric motors;
- fan performance;
- fan design methods;
- fan efficiency.

4.1 MEASUREMENT AND TEST

Stevens and Gyuro (2015) studied the laboratory-to-laboratory variation in measured fan performance for a single fan when tested in multiple laboratories. The purpose of this study was to advance the community's understanding of the impact of test system geometry on fan performance. Three fans were tested in each laboratory, a centrifugal fan, a tube-axial fan and a vane-axial fan. All laboratories incorporated multi-nozzle chambers. The results from each laboratory matched well for both the centrifugal and vane-axial fans. However the laboratory to laboratory variation in the tube-axial fan performance was significant. This indicates that fan outlet swirl has a significant impact on measured fan performance. A conclusion of the study was that there is a correlation between fan outlet swirl and the ratio of fan outlet area to the area of the test chamber. The sensitivity of measured fan performance to this ratio is more significant than has historically been assumed.

Sampath and Katz (2015) utilised phase-locked particle image velocity measurements when studying an automotive fans wake flow structure and turbulence level. The particle image velocity measurements were facilitated by manufacturing the studied fan from acrylic and testing it in an aqueous solution with the same refractive index. Consequently, fan blades were near 'invisible' facilitating particle image velocity measurements. Phase-locked data was analysed, with phase averaged mean velocity and turbulence distributions then being derived. The particle image velocity measurement technique was therefore able to resolve features in highly turbulent regions of the flow-field. In so doing the measurements provided an insight into the flow-field physics of the blade wake region.

Corsini *et al* (2015c) studied the practicality of using low-cost pressure sensors in an acoustic stall detection system. The study compared measurements taken using a low-cost dynamic transducer and a high-precision

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piezoelectric sensor costing approximately 100 times more than the dynamic transducer. Measurements with each transducer were taken as an axial fan was driven into rotating stall. The measurements were then analysed, with the data recorded using each transducer being shown to be sensitive enough to enable the identification of features within the measured signals indicative of rotating stall. The authors therefore concluded that the low-cost dynamic transducer was a good candidate for incorporation into a stall-warning system suitable for application monitoring air movement fans.

Moreau *et al* (2015) conducted experimental and numerical tests in an effort to characterise the noise mechanisms of an air movement fan. Measurements were made with a fan rotating and when static, whilst ensuring that in both cases Mach number and Reynolds number were kept constant. This combination of test methods facilitated the generation of a unique aero-acoustic data set that the authors then used to characterise fan blade trailing-edge noise. The comparison between static and rotating data sets enabled the authors to conclude that fan casing pressure was not influenced significantly by the effects of rotation in the blade trailing edge region. The test bed developed by the authors for making the experimental and numerical noise measurements was concluded to be suitable for general application when characterising the acoustic performance of a wide range of air movement fans.

4.2 ELECTRIC MOTORS

Park *et al* (2015) conducted an aerodynamic characterisation of a cooling fan used in a low-voltage electric motor. Using a Reynolds-averaged Navier-Stokes simulation the authors optimised their computational approach and its associated boundary conditions. The authors were able to use their computational approach to perform a parametric study, predicting the sensitivity of fan performance to changes in fan geometry. They identified that the flowrate though a fan could be increased by reducing the intensity of secondary flow features though the impeller blade-to-blade passages.

Ogushi *et al* (2015) studied the vibration and acoustic characteristics of an air movement fan motor that arise as a consequence of electromagnetic forces. The authors specifically focused on motors combined with the fan impeller, in contrast to the more usual configuration of a stand-alone motor driving an impeller. When studying combined motor and impeller performance the authors observed that design engineers classically study fluid dynamics, electromagnetic dynamics or structural dynamics. However, they have generally been studied in isolation and not in combination. When the motor is combined with the impeller both fan noise and vibration is driven by a combination of electromagnetic, mechanical and fluid forces. The authors concluded that tonal noise peaks were maximised when a harmonic frequency of the electromagnetic force and a fan axial natural frequency matched.

Pfaff (2015) presented an analysis process for thermal assessment of motors when designed as an integral part of a fan. The authors observed that when attempting to conduct a thermal analysis, magnetic performance is a function of temperature. However, temperature is a function of the losses in the thermal system and consequently motor losses and temperature are interdependent. The authors present a thermal analysis process that models the thermal conductivity of the materials involved. In so doing they were able to develop an iterative thermal analysis process able to bring magnetic design, losses and associated temperature rise into equilibrium. The resulting thermal analysis process facilitates the optimisation of motor magnet design.

Kaufman (2015) studied torsional resonance problems associated with variable frequency driven fans. The use of variable frequency drives has become common in the control of increasingly powerful fans. A variable frequency drive is able to control motor in-rush current and fan speed reducing the capital cost of electrical cables and fan operating cost. However, there are negative aspects associated with the use of variable frequency drives, most problematic of which are mechanical resonances associated with torsional natural frequencies. The research presented by the author characterises the impact of the frequency of variable frequency drive electrical switching on variable frequency drive output. The author identifies that switching frequency induced harmonics in the variable speed drive output induce torsional vibrations in the motor that have the potential induce a mechanical failure in the motor to fan shaft coupling.

4.3 FAN PERFORMANCE

Cyrus (2015) studied the design of axial fans intended for application in forced- and induced-draft power plant application with the twin objectives of maximising fan pressure developing capability and efficiency. The author presents

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