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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.

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 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 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.

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.

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.

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 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 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 examples of the optimisation of induced draft axial fan geometry. The objective of the optimisation was to evaluate the viability of higher pressure and higher flow axial fan designs. The author was able to demonstrate to viability of replacing a historic two-stage fan with a single-stage design, whilst maintaining fan diameter and speed constant.

Wilkinson and Van Der Spuy (2015) studied the performance of large diameter axial flow fans used in air-cooled condensers. These large diameter fans consume the majority of air-cooled condenser power and consequently fan efficiency is a source of competitive advantage. The authors assert that loss mechanisms associated with blade tip-to-casing flow-field featured have a primary impact on overall fan efficiency. They characterise the change in fan performance with changing blade tip-to-casing clearance and evaluate the effect of a blade-tip appendage on fan performance. The authors conclude that blade tip-to-casing clearance has a first-order impact on fan efficiency and that a blade tip-appendage may be used to minimise the performance penalty associated with a large blade tip-to-casing gap.

Spinola *et al.* (2015) studied the aerodynamic performance of a cross-flow fan while varying fan rear-wall shape and inlet conditions. Cross-flow fans are widely used in industrial and domestic applications in which the radial space availability for fan installation is limited. Unlike other types of fans, the cross-flow fan internal flow-field is characterised by an eccentric vortex resulting from blades circulation. In the research reported in this paper, the effect of suction side volume limitation in the radial direction on the performance developing capability of a small cross-flow impeller is experimentally investigated. The impact of changing geometry on fan performance was evaluated. The resulting characterisation provides design engineers with a basis for predicting cross-flow fan performance.

Bayrakdar *et al.* (2015) present an investigation into the effect of impeller design on cross-flow fan aerodynamic and aero-acoustic performance. The authors present a parametrically designed impeller, with the impact of flexing each parameter on fan flow-rate and far-field noise being experimentally verified. In so doing the authors provide an insight into the sensitivity of cross-flow fan performance to changing geometry that in turn facilitates the minimisation of noise while maximising fan flow-rate.

Zou *et al.* (2015) conducted a numerical analysis of a floor-standing air conditioning unit incorporating a novel reversible inflow and exhaust flow design. Conventional floor standing air conditioning units incorporate an inlet at the base and an outlet at the top of the unit. This configuration is generally effective, but does not supply cooled air below human knee height. The authors aim to improve this situation by advocating new fan technology incorporating an independent reversible flow fan design. The reversible design allows the air conditioning unit in forward mode to supply cooling air from the top and in reverse mode to supply heated air to the bottom. The resulting air-conditioning unit was shown by the authors to improve indoor air quality whilst also reducing energy consumption.

Saul*et al.* (2015) present a method for predicting fan performance that takes into account the effects of compressibility on flow-field loss mechanisms. The fan laws provide a good estimate of fan performance when the blade-to-blade flow-field is essentially incompressible. However, when compressibility effects become significant the error associated with using the fan laws to predict fan performance become progressively more significant. In the research reported in this paper the authors present a series of empirical correction factors. The authors experimentally verify the accuracy of their correction factors, concluding that they provide design engineers with a basis for predicting compressible fan performance.

Bode *et al.* (2015) analysed the impact of skewed inlet boundary layers on the aerodynamic performance of a two-dimensional cascade of highly loaded axial fan blades. The authors conduct their analysis using a numerical investigation two-dimensional compressor cascade performance. The two-dimensional cascade flow-field may be characterised as similar to the flow-field though the hub section of a highly loaded single-stage low-speed compressor. In the research reported in this paper the authors identify that the boundary layer leaving the rotor hub has a velocity deficit that is then re-energised as it enters the stator. The authors conclude that overturning of the hub boundary layer is less with a skewed inlet boundary layer, reducing hub passage vortex intensity. This reduction occurs as a consequence of interaction between the end-wall and blade suction surface boundary layer flow, resulting in lower loss though the blade-to-blade passage.

4.4 FAN DESIGN METHODS

Nelson (2015) proposed that fan selection may be improved through the use of an extended range of performance curves that present fan aerodynamic and acoustic performance as a set of iso-curves. The author asserts that air performance curves are the locus of pressure-flow states achievable over a range of loads for a given speed and therefore may be characterised as “iso-speed” curves. Similarly the “iso-acoustic” curve may be conceptualised as the locus of pressure-flow states achievable over a range of loads for a given acoustic emission. Finally the “iso-power” curve may be conceptualised as the locus of pressure-flow states achievable over a range of loads for a given power consumption. By presenting fan performance as a set of speed, acoustic and power iso-curves, the designer is provided with a method to simultaneously optimise fan noise, energy efficiency and performance.

Vogel *et al.* 2015) present an axial fan blade inverse design method developed to improve prediction of fan off-design performance. The design method models both design and off-design fan performance using a calculation of radial equilibrium, a streamline curvature method and a surface vorticity method. The resulting design method is then used by the authors to design the geometry of a fan from an initial required fan performance. Performance of the resulting geometry is then validated numerically, with the agreement between the design intent and predicted performance being concluded to be good.

Schanzle *et al.* (2015) present a method for the optimisation of complex ventilation systems with the aim of minimising ventilation system energy consumption over a range of operating points. The authors contend that the fans applied into ventilation systems are classically selected for operation at a peak pressure operating point. However, when the actual distribution of operating points is considered the authors advocate for an array of smaller fans as being a more efficient solution. In so doing the authors are not specifically arguing in favour of parallel fan installations. However they do contend that optimising component performance does not necessarily improve system performance. The authors present a system optimisation method that aims to optimise system and not component efficiency from a pre-defined set of available ventilation system components.

4.5 FAN EFFICIENCY

Bamberger and Carolus (2015a) studied the achievable total-to-static efficiency of an axial fan using an optimisation process trained using a database of 13,000 fan characteristics. The authors adopt a theoretical approach to the identification of the optimal blade hub-to-tip ratio and optimal swirl distribution facilitating the prediction of fan exit loss. However, the authors contend that a more accurate prediction of exit loss requires a more advanced methodology. In the research presented in this paper the authors estimate the achievable total-to-static efficiency using a novel optimization method based on a multi-layer perceptron target function. The multi-layer perception target function was trained using the database of 13,000 fan characteristics. The authors concluded that at most design points, the difference between theoretically optimised and multi-layer perception optimised efficiency is primarily due to hydraulic losses. However, at some design points the multi-layer perception optimised fans also feature significantly higher exit losses.

Aldi *et al.* (2015b) contend that small industrial fan efficiency is generally low compared to the requirements of current and forthcoming regulatory requirements. In response they propose a three-dimensional optimisation process to improve fan efficiency. The authors present a mono-dimensional design and three-dimensional optimisation method based on the use of numerical simulations. They predict the performance of an existing Sirocco fan and a backward-curved centrifugal fan, advocating that an optimised backwards-curved centrifugal fan has the potential for significantly higher efficiency than the existing or optimised Sirocco fan. An experimental assessment of the optimised backwards-curved centrifugal fan is demonstrated to have higher efficiency. Critically the efficiency is high enough to exceed the minimum allowable efficiency mandated by European Commission Regulation 327.

Martin (2015) considers the issues with retrofitting in-service fans with new impellers to improve efficiency. He proposes strategies that will help avoid post-retrofit failures. He then clarifies the factors a fan operator should consider when deciding if a potential upgrade candidate can be retrofitted in a technically viable manner. The author reviews the success of retrofitted fans in achieving their target efficiency through the use of two mini case studies; one which met the specified performance expectations and one which did not. The author concludes by considering the practical limitations fan operators should take into account and the role that numerical methods can play in a fan operator’s decision making process.

4.6 CURRENT ISSUES IN FAN TECHNOLOGY

The papers focusing on measurement and test collectively illustrate that innovation in instrumentation and experimental measurement techniques is both possible and able to make a contribution to the community. As computational methods become more sophisticated, the need increases for experimental dataset to validate these them. The research of Sampath and Katz (2015) illustrates that particle image velocimetry may be applied successfully to study the flow-field features at play within the blade-to-blade passage of an air movement fan. The research of Corsini *et al.* (2015c) illustrates that it is possible to manufacture a stall detection system of low enough cost for application with air movement fans intended for light industrial applications. The research of Moreau *et al.* (2015) illustrates that acoustic measurement techniques first developed within the aerospace community can be applied successfully to the study of air movement fan acoustic emissions.

The papers focusing on electric motors collectively illustrate that the design and integration of electric motors into air movement fans is associated with a range of challenges. These challenges can result in sub-optimal motor design for the application, and in extreme cases in-service failure of the motor or fan into which the motor is integrated or driving. The research of Park *et al.* (2015) illustrates that air movement fans intended to cool electric motors are associated with their own set of constraints that must be taken into account when designing and optimising fan geometry. The research of Ogushi *et al.* (2015) illustrates complexity of the physics responsible for motor acoustic emissions when the motor comprises an integral part of the fan. They report research clarifying how tonal noise may be predicted and motor geometry optimised to avoid tonal peaks. The research of Pfaff (2015) illustrates the challenges associated with the design and optimisation of a motor when the motor comprises an integral part of the fan. Pfaff (2015) provides designers with a method for optimising the combined motor and fan design. The research of Kaufman (2015) illustrates that inappropriate application of variable frequency drives has resulted in failure of fan and motor couplings, and provides guidelines for appropriate specification of variable frequency drives to avoid in-service failures of couplings.

The papers focusing on fan performance collectively illustrate that performance prediction and the optimisation of fan geometry to maximise performance remain an issue for the air movement fan community. The research of Cyrus (2015) illustrates that the application of current design methods can facilitate a significant increase in fan performance. They illustrate their point by replacing a historic two-stage fan with a new single-stage design operating at the same duty point. The research of Wilkinson and Van Der Spuy (2015) illustrates that the efficiency of very large low-speed axial fans used in air-cooled condensers is significantly reduced by large blade tip-to-casing gaps. They demonstrate that a blade tip-to-casing appendage may be used to mitigate the performance penalty associated with large blade tip-to-casing gap size. The research of Spinola *et al.* (2015) illustrates that performance prediction methods developed for application with axial or centrifugal fans do not apply directly to cross-flow fan performance prediction. They characterise the change in cross-flow fan performance with changing fan geometry. The research of Bayrakdar *et al.* (2015) also focuses on cross-flow fan performance prediction, presenting a method for optimising cross-flow fan aerodynamic and acoustic performance. The research of Zou *et al.* (2015) studies system, rather than fan performance prediction, evaluating the performance of a novel air conditioning unit configuration. The research of Saul *et al.* (2015) provides designers with a method for predicting fan performance when compressibility effects become significant. The research of Bode *et al.* (2015) characterises the effect of skewed inlet boundary layers on fan performance.

The papers focusing on fan design methods collectively illustrate that design methods can extended to facilitate the optimisation of fan geometry for operating at off-design conditions. The research of Nelson (2015) illustrates that the conventional presentation of fan performance characteristics may be expanded to facilitate optimum aerodynamic and acoustic fan selection when selecting a fan at different locations on its performance characteristic. The research of Vogel *et al.* (2015) illustrates that an inverse-design method may be used to optimise the geometry of a fan intended for operation at both a design and off-design operating points. The research of Schanzle *et al.* (2015) focuses on system, rather than fan performance, optimising system efficiency over a range of operating points.

The papers focusing on fan efficiency collectively illustrate that current and forthcoming regulatory targets for minimum fan efficiency are driving the air movement fan community to develop methods for improving fan efficiency. The research of Bamberger and Carolus (2015a) illustrates that a novel optimisation tool can be used to maximise fan efficiency. The research of Aldi *et al.* (2015b) illustrates that a one-dimensional fan design tool may be complimented by a three-dimensional optimisation tool that together may be used to maximise fan efficiency. The research of Martin (2015) studies the practical problems of predicting the in-service efficiency of a replacement impeller when retrofitting a historic installation. The author presents a method for assessing the costs and benefit associated with retrofitting a historic installation with a new impeller.

5.0 FAN NOISE

The air movement fan community is focused on the modelling and prediction of fan noise. A desire to design both more aerodynamically efficient and lower noise fans is an overarching driver when modelling and predicting fan noise, Sheard (2014a). There is consequently increasing interest within the air movement fan community is modelling and prediction methods that may be practically applied during fan design and development processes. Those researchers studying fan noise have focused their effort into nine areas of endeavour:

- heating, ventilation and air conditioning of cars;
- tip leakage noise of axial fans;
- signal processing for noise source localisation and characterisation;
- noise of centrifugal fans;
- prediction of axial fan noise by hybrid method;
- sound quality;
- Lattice Boltzmann methods;
- tonal noise modelling;
- installation effects.

5.1 HEATING, VENTILATION AND AIR CONDITIONING OF CARS

Jung *et al.* (2015) study the effect of blade sweep on the far-field noise of an axial fan intended for automotive application. The authors' used an unsteady Reynolds-averaged Navier-Stokes based computational method to predict the flow-field through a centrifugal fan with three blade types; forward swept, backward swept and straight. Output from the flow-field simulations was used as an input for a Ffowcs-Williams-Hawkings acoustic analogy to predict fan far-field noise. The authors used results from the flow-field simulation and Ffowcs-Williams-Hawkings acoustic analogy to identify the near-field aerodynamic origin of far-field fan noise. They concluded that the centrifugal fan with forward swept blades was 2 to 3 dB quieter than the fan with either backward swept or straight blades as a direct consequence of the blade forward sweep.

Legros *et al.* (2015c) present an inverse method for prediction far-field fan noise based on a characterisation of noise sources that they linked back to near-field flow-field features. The method enables a fan designer to characterise the impact of near-field flow-field features on fan far-field noise. The authors' inverse design method focuses on the definition of acoustic source terms. They used the Euler equations to derive acoustic source terms, with the validity of the source terms being established experimentally. The resulting inverse design method provides fan designers with a tool to generate a fan design using a far-field noise target as an input to the design process.

Legros *et al.* (2015b) present a method for predicting the spectrum and far-field broadband noise of a fan when embedded in a complex system. Predicting the spectrum and far-field broadband noise of a fan when embedded in a complex system is challenging. The authors do so by identifying and modelling acoustic sources and pathways from the source to a far-field reception point. At the point of reception a performance metric is developed through a synthesis of sound pressure level and sound power level. This acoustic synthesis provides a tool fan designers can use to predict fan and system far-field noise. The authors apply their acoustic synthesis to a fan intended for automotive application. They concluded that the acoustic synthesis was effective as a consequence of taking into account system effects, including fan installation effects.

Bennouna *et al.* (2015) present a method for characterising the components of a heating, ventilation and air conditioning system and in so doing facilitate the prediction of system spectrum and far-field broadband noise. The authors' model the elements within the system and model the acoustic properties of the elements that comprise the system. The resulting design method can be used to establish the acoustic consequences associated with changing the geometry of different elements within the system. The design method utilises acoustic passive properties represented by a multi-modal scattering matrix, and then goes on to characterise the associated aero-acoustic sources. The aero-acoustic sources were deduced from measurements of source vector and pressure loss. The design method is then validated experimentally, in so doing providing both fan and system designers with a method for optimising system performance.

The papers focusing on heating, ventilation and air conditioning systems of cars collectively illustrate that minimising system noise requires a design engineer to optimise both system components and geometry of the fan embedded within the system. The research of Jung *et al.* (2015) illustrates that the optimisation of blade sweep can reduce significantly the far-field noise of a fan intended for automotive application. The research of Legros *et al.* (2015c) illustrates the effectiveness of an inverse design tool that facilitates the development of fan geometry intended to achieve a specific far-field noise target. The research of Legros *et al.* (2015b) presents a method for predicting fan far-field noise when the fan is embedded in an automotive heating, ventilation and air conditioning system. The research of Bennouna *et al.* (2015) illustrates a method for acoustically characterising each element of an automotive heating, ventilation and air conditioning systems that facilitates acoustic optimisation of that system.

5.2 TIP LEAKAGE NOISE OF AXIAL FANS

Zhu and Carolus (2015) conducted an experimental and numerical study of axial fan blade tip-to-casing clearance induced noise. The blade tip-to-casing leakage vortex is classically characterised as a near-field flow-field feature that constitutes the aerodynamic origin of a significant proportion of fan far-field noise. The research reported in this paper revisits the physical flow mechanisms underpinning the near-field aerodynamic origin of fan far-field noise. The authors utilise a numerical simulation incorporating the unsteady and compressible Lattice-Boltzmann method to conduct a direct and simultaneous prediction of both the fan aerodynamic and acoustic characteristics. The authors conclude that the agreement between measured and simulated overall fan performance and far-field noise was reasonable, giving confidence in the accuracy with which the near-field flow-field is simulated. From an analysis of the near-field flow-field simulation the authors were able to conclude that the intensity of the blade tip-to-casing leakage vortex increases with increasing blade tip-to-casing gap size. It also increases when the fan is operated away from its design point.

Allam and Åbom (2015) studied the reduction in an automotive radiator cooling fans acoustic emissions when fitted with micro-perforated plates and quarter-wave resonators. Automotive fans are classically considered to be a significant vehicle noise source, an issue exacerbated with the shift towards electric cars. Electric cars eliminate noise sources associated with an internal combustion engine, and are therefore intrinsically quieter making fan noise proportionally more important. The authors' present an experimental evaluation of near-field noise control by using micro-perforated plates and quarter-wave resonators. By optimising micro-perforated plate and quarter-wave resonator geometry they were able to reduce fan noise by between 1.5 and 4.5 dB(A) dependent on fan speed.

Lee and Bolton (2015) also studied the effect of micro-perforated plates on an axial fans blade tip-to-casing clearance generated acoustic emissions. The authors make the same point made by Zhu and Carolus (2015); the blade tip-to-casing leakage vortex is a near-field flow-field feature that constitutes the aerodynamic origin of a significant proportion of fan far-field noise. In the research reported in this paper the authors reduce fan far-field noise by incorporating micro-perforated plates into a fan casing in the blade tip-to-casing gap. The authors concluded that the micro-perforated plates resulted in a reduction in fan far-field tonal and broadband noise. However, the impact on fan aerodynamic performance was concluded to be negligible. They therefore advocate the use of micro-perforated plates when the design engineer's objective is to minimise fan far-field noise.

The papers focusing on axial fan tip-leakage noise collectively illustrate that near-field aerodynamic features in the blade tip region constitute the origin of the dominant components within a fans far-field noise spectrum. The research of Zhu and Carolus (2015) illustrates that a numerical simulation may be used to characterise the far-field acoustic consequences of changes in both blade tip-to-casing gap size and fan operating point. The research of Allam and Åbom (2015) illustrates that the application and optimisation of micro-perforated plates and quarter-wave resonators in the blade tip region can effectively minimise fan far-field noise. The research of Lee and Bolton (2015) also studied the impact of micro-perforated plates when installed in the casing over fan blades. They concluded that the application of micro-perforated plates minimises fan far-field noise.

5.3 SIGNAL PROCESSING FOR NOISE SOURCE LOCALISATION AND CHARACTERISATION

Finez *et al.* (2015) compared the effectiveness of three methods for identifying the near-field noise sources responsible for fan far-field broadband noise. The authors characterise a fans acoustic pressure field and then present a mode decomposition technique for calculating the cut-on mode amplitudes for each discrete frequency using surface pressure measurements. The authors present three cross-spectral matrix techniques, using numerical simulations to verify the relative performance of each technique. After characterising the three techniques, the authors compare the calculated broadband noise and spectrum with measurements, concluding that the agreement between the two was reasonable.

Horvath *et al.* (2015) studied fan near-field noise sources that manifest themselves in the far-field as on-axis tonal noise. The research reported in this paper presents a study of rotating source identifier beamforming maps for an axial flow fan. The authors observed that noise sources localized to the fan axis by the beamforming methods have classically been attributed to the motor. They conclude that noise sources emanating along the fan axis in actuality emanate from a range of locations and not only the fan motor.

Sack *et al.* (2015) study the aero-acoustic behaviour of an aircraft air conditioning system, and propose strategies to minimise acoustic emissions. The authors characterise an aircraft air conditioning system as a network of passive elements that scatter existing sound fields and active elements that emit noise. They present strategies to abate aircraft air conditioning system acoustic emission. The strategies are based on a linear multi-port model incorporating direction dependent transmission and reflection coefficients for the propagating wave modes and sound generation. These coefficients were derived by the authors both numerically and experimentally, with the agreement between the two being concluded to be reasonable.

Herold and Sarradj (2015) present a virtual rotating microphone array that they use to identify the noise sources associated with a rotating axial fan. In so doing they are able to separate rotating and stationary noise sources. The concept of a virtual rotating microphone array was developed to facilitate the characterisation of rotating noise sources as if they were stationary. The array algorithm is based on cross-spectral matrix evaluation. The possibility of separating stationary and rotating sources using this method was considered by the authors, and prerequisites for its application identified. They validated the method experimentally using a microphone array, concluding that the virtual rotating microphone array provides an effective way of identifying rotating noise sources.

Wang *et al.* (2015) present methods for localising both tonal and broadband noise sources associated with two axial fans operating in series. When two axial fans are operated in series they interact both aerodynamically and acoustically. The research presented in this paper comprises an experimental characterisation of two axial flow cooling fans intended for application in an electronic cooling system. The authors' study discrete tonal noise across a range of fan speeds in an effort to distinguished noise sources associated with each of the two fans and interaction between the two. They use a time-based stretching synchronous averaging technique when conducting acoustic directivity measurements and noise source analysis. The authors use the results of their analysis to optimise the system within which the two fans are embedded, reducing fan far-field noise by 2.5 dB.

The papers focusing on signal processing for noise source localisation and characterisation collectively illustrate that the developed modelling techniques are able to predict with reasonable accuracy the far-field acoustic consequences of near-field noise sources. The research of Finez *et al.* (2015) illustrates the effectiveness of three methods for identifying the near-field noise sources responsible for fan far-field broadband noise, concluding that calculated broadband noise and spectrum were in reasonable agreement with measurements. The research of Horvath *et al.* (2015) illustrates that a range of near-field noise sources were responsible for fan on-axis far-field noise. The research of Sack *et al.* (2015) presents numerical strategies to predict and minimise aircraft air conditioning system acoustic emission with the agreement between predicted and measured noise levels being concluded to be reasonable. The research of Herold and Sarradj (2015) illustrates that a virtual microphone array can be used to identify the rotating noise sources associated with a rotating fan impeller. The research of Wang *et al.* (2015) illustrates that when two fans operate in series there are interaction based noise sources in addition to those associated with each fan. By modelling both individual and interaction noise sources the authors were able to minimise fan far-field noise.

5.4 NOISE OF CENTRIFUGAL FANS

Iwase *et al.* (2015) predicted the flow-field though the centrifugal fan of an air conditioning unit using a large eddy simulation in an effort to predict the aerodynamically induced fan far-field noise. The research reported in this paper presents a study of the flow-field though the impeller of a centrifugal fan utilising a large eddy simulation to predict the unsteady pressures though the fan. The unsteady pressures are then used to predict fan far-field noise. Near-field unsteady pressure was used to calculate fan far-field noise using Curle's equation, a process facilitated by assuming that noise source were acoustically compact. The authors concluded that the developed method constitutes an effective tool for predicting fan far-field noise.

Koyama *et al.* (2015) predicted the flow-field though a bi-directional radial fan, and then compared the predicted flow-field features with experimentally measured fan far-field noise. The research reported in this paper clarified the relationship between the flow-field though the studied radial fan and fan far-field noise. The authors were able to use the analysis to identify noise sources associated with the fan that then enabled them to optimise fan geometry. The authors concluded that blade profile, inlet and outlet duct geometry has a primary impact of fan far-field noise. The authors' optimisation resulted in an experimentally verified 2 to 3 dB reduction in fan far-field noise.

Sasaki and Onomichi (2015) predicted the flow-field though a centrifugal fan whilst operating in rotating stall, concluding that the rotating stall cell rotated at 40 percent fan speed manifesting itself acoustically as seven pseudo blades. The research reported in this paper focuses on the performance of two impellers, identical with the exception of shroud design. A numerical simulation of the flow-field though the impeller producing the higher pressure identified a rotating stall cell. The authors were able to experimentally verify that the stall cell was responsible for the increase in fan broadband noise.

Hayashi *et al.* (2015) study the acoustic performance of a backward-curved centrifugal fan impeller when installed in a square casing typical of those utilised in air conditioning systems. The authors were surprised to find that the efficiency of the studied fan at high flow-rate was better when the impeller was installed in the air conditioning system than a scroll casing. The research they report in this paper presents the results of their study of the interaction between the impeller and the air conditioning system. The authors concluded that far-field noise was associated with different noise sources at different frequency ranges. They end the paper by identifying the primary drivers of fan far-field noise when an impeller is installed in an air conditioning system.

The papers focusing on centrifugal fan noise collectively illustrate the challenges associated with predicting centrifugal fan acoustic emissions. The computational effort required to model the near-field flow-field with sufficient accuracy to predict centrifugal fan far-field noise is increasingly available to the air movement fan community, but remains formidable. The research of Iwase *et al.* (2015) illustrates that a large eddy simulation of the flow-field though a centrifugal fan may be used to predict with reasonable accuracy centrifugal fan broadband noise and spectrum. The research of Koyama *et al.* (2015) illustrates that the noise sources within a radial fan can be identified with sufficient accuracy to facilitate the optimisation of fan geometry to effectively minimise fan far-field noise. The research of Sasaki and Onomichi (2015) illustrates that it is possible to predict the far-field acoustic consequences associated with driving a centrifugal fan into rotating stall. The research of Hayashi *et al.* (2015) illustrates that centrifugal fan far-field noise changes significantly when the same impeller is installed in a casing or in an air conditioning unit. The authors were able to identify the near-field noise sources responsible for fan far-field noise in each application.

5.5 PREDICTION OF AXIAL FAN NOISE BY HYBRID METHODS

Carolus *et al.* (2015) present a data set of aerodynamic and acoustic measurements that collectively characterise the performance of a low pressure axial fan. Fan geometry has been made available in the public domain as has details of the test rig used to obtain the data set. The geometry and data set is provided as a service to members of the air movement fan community, to assist them in developing numerical methods to predict fan aerodynamic or acoustic performance. The authors have a particular interest in fostering the development of new steady and unsteady aerodynamic and aero-acoustic prediction methods.

Kucukcoskun *et al.* (2015) developed a semi-analytical modelling technique for predicting the broadband noise generated by a low-speed axial fan. The reported research identifies two broadband noise mechanisms; leading edge noise and trailing edge noise. The authors contend that the former is associated with impingement of turbulent flow onto the leading edge of fan blades. The latter is associated with the development and separation of blade suction and pressure surface boundary layers. The authors predicted the fan blade-to-blade flow-field, using the results as input to a theoretical method, predicting both upstream and downstream turbulence spectrum. The authors then predict fan broadband noise using an acoustic transfer vector approach embedded within a boundary element method framework, concluding that the predicted far-field noise was in reasonable agreement with experimentally measurements.

Chumakov *et al.* (2015b) studied the practical problems associated with use of a large eddy simulation of an axial fans blade-to-blade flow-field to predict the acoustic emissions from both stationary and rotating surfaces. The research reported in this paper utilises a local mesh adaption technique to concentrate the computational mesh in the near vicinity of the fan blade suction surface, pressure surface and turbulent wake. Unsteady velocities and pressures are predicted in these three critical regions, from which fan acoustic emissions are projected to the duct, up and downstream using the linear Ffowcs Williams-Hawkings equation. Acoustic reflection in the duct is accounted for using a massively parallel Ffowcs Williams-Hawkings and boundary element based method. The resulting prediction of broadband noise was concluded by the authors to be in good agreement with experimentally measured fan far-field noise.

Becher *et al.* (2015) conducted a numerical study into the effect of forward and backward axial fan blade sweep on the acoustic performance of a cooling fan intended for automotive application. The research reported in this paper presents an optimisation approach to the ventilation system though a consideration of the acoustic contribution of each element in the system. Within that system the authors assert that the fan is the dominant noise source that they go on to model using a hybrid computational method. The hybrid method combines a Reynolds-averaged Navier-Stokes simulation of the flow-field with the Ffowcs Williams-Hawkings equation then being used to predict fan far-field noise. The authors predict the far-field noise of three fan configurations. The predicted fan far-field noise was then compared with measured noise and concluded to be in good agreement.

Guedel and Robitu (2015) present the results of a two-part study. First to experimentally measure axial fan broadband noise. Second to predict broadband noise using numerically predicted unsteady pressures as input to and empirical acoustic model. In the research reported in this paper the authors present unsteady pressure measurement made on the rotating blade on an axial fan. These unsteady pressure measurements were then used as input to an acoustic model of blade trailing edge noise. The authors go on to clarify the relative importance of trailing edge and blade tip-to-casing leakage flow induced noise. They then present the results of a Reynolds-averaged Navier-Stokes simulation to predict the unsteady pressure near the blade surface and close to the trailing edge. They compare the measured and predicted blade unsteady pressures, concluding that they are in reasonable agreement. The authors' are therefore able to conclude that the predicted blade unsteady pressures can be used as an input to their acoustic model.

Grasso *et al.* (2015) present a semi-empirical acoustic model developed for predicting axial fan broadband trailing-edge noise. Trailing edge noise is generated by the scattering of blade suction and pressure surface boundary layers into acoustic waves. The research reported in this paper predicts the trailing edge noise of an axial fan, with the data base of experimental measurements generated during the research being made available in the public domain. By making the database available the authors' intent is to support the development of computational methods for predicting fan noise across the wider community. The authors own computational approach comprises a steady Reynolds-averaged Navier-Stokes simulation of the blade-to-blade flow-field combined with a semi-analytical acoustic method. The blade suction and pressure surface wall-pressure spectrum is then derived in the trailing edge region from a boundary layer reconstruction model that is then used to predict fan far-field noise. Comparisons between experimentally measured and predicted fan far-field noise were concluded to be in reasonable agreement.

Legros *et al.* (2015a) present a technique for predicting axial fan broadband noise based on the experimental localisation of noise sources followed by the application of a numerical method to compute their propagation. In the research reported in this paper the authors develop a novel fan far-field noise synthesis approach. The synthesis approach is based on an identification of noise sources located on the fan blades using experimentally measured data. The resulting noise sources are represented by a distribution of volumetric forces contained within a volume close to the blades. Fan far-field noise is then calculated by propagating each noise source, both using an analytic approach and a computational approach. The authors conclude by evaluating the significance of noise sources to the resulting fan far-field noise.

5.6 SOUND QUALITY

Schneider and Feldmann (2015) evaluated the psychological impact of fan noise as perceived by human observers. The air movement fan community typically characterises fan acoustic emissions using an assessment of overall fan noise and spectra. However, a human observer may perceive differently the noise from two fans with a similar overall noise level and spectra. In the research reported in this paper the authors studied the reaction of participants as they listened to the noise from axial and radial fans when installed in a range of applications. They concluded that overall noise level and spectrum were important parameters when characterising fan acoustic emissions. However the magnitude of single tones was also important. Additionally as a fan approached stall its acoustic emissions became more chaotic, an effect that human observes perceived negatively even if average overall noise and spectra remained constant.

Minard *et al.* (2015) present a design tool that they then apply to the design of heating, ventilation and air conditioning systems intended for application in hybrid or electric cars. The reported research presents a computational tool available to engineers designing new heating, ventilation and air conditioning systems. The tool models the system within which a fan is embedded, with a resulting prediction of system noise within the car. The authors predict noise within the car by utilising an additive synthesis algorithm able to predict both tonal and broadband components of system noise. The resulting modelling tool was concluded to be able to predict well the effect of changes in fan and system geometry on noise within the car.

5.7 LATTICE BOLTZMANN METHODS

Lattice Boltzmann methods are a class of computational fluid dynamics methods for fluid simulation. Instead of solving the Navier-Stokes equations, the discrete Boltzmann equation is solved to simulate the flow of a Newtonian fluid with collision models such as Bhatnagar-Gross-Krook. By simulating streaming and collision processes across a limited number of particles, the intrinsic particle interactions makes evident a microcosm of viscous flow behaviour applicable across the greater mass.

Lattice Boltzmann methods are a relatively new simulation technique for complex fluid systems and have attracted interest from researchers. Unlike the traditional computational fluid dynamics methods, which solve the conservation equations of the macroscopic properties mass, momentum, and energy numerically, Lattice Boltzmann methods model the fluid consisting of imaginary particles. These imaginary particles propagate and collide over a discrete lattice mesh. Due to its particulate nature and local dynamics, Lattice Boltzmann methods have advantages over other conventional computational fluid dynamics methods, especially in dealing with complex boundaries and incorporating microscopic interactions. In his key-note lecture Dr Moreau stresses the effectiveness of Lattice Boltzmann methods, specifically advocating their use in preference to unsteady Reynold-averaged Navier-Stokes simulations, Moreau (2015).

Kusano *et al.* (2015) conducted a numerical analysis of the blade-to-blade flow-field though a low-pressure axial fan. The reported research presents the authors Lattice Boltzmann based method that models the blade pressure surface, suction surface and duct using an immersed boundary scheme. The authors captured the blade-to-blade flow-field features at the blade tip as a consequence of their grid refinement in the blade tip region. They assert that the far-field noise of the studied fan is dominated by the unsteady flow-field features in the blade tip region. The authors predicted the blade-to-blade flow-field using both a detached eddy simulation and a simulation based on the Lattice Boltzmann method. They concluded that agreement between the two was good, validating the developed Lattice Boltzmann method.

Sturm *et al.* (2015) predicted the blade-to-blade flow-field though an axial fan and the full test rig within which it was installed. The simulation was particularly noteworthy as the authors predicted the flow-field over the 150 second time period. They then went on to predict fan far-field noise using a Lattice Boltzmann method. Fan far-field noise is classically measured when the fan is installed in a test rig with a large volume upstream of the fan inlet. However, the size of the upstream volume has an impact on measured fan far-field noise. Even when the volume is 1000 time that of the fan, low-speed recirculating flow-field structures develop within the volume. These recirculating structures affect the inlet flow into the fan, with the interaction of these structures with the fan resulting in tonal noise that is a product of the test rig and not the fan. The authors concluded that large scale flow-field featured within the upstream volume have a distinctive impact on the fans far-field tonal noise.

Pain *et al.* (2015) use a Lattice Boltzmann numerical method to predict the flow-field through a centrifugal fan and its associated acoustic emissions. The numerical simulations utilize an optimization algorithm that facilitated design of a passive noise control device the authors chose to name a flow-obstruction. This flow-obstruction is located in the system within which the fan is embedded, immediately upstream of a heat exchanger. The optimization algorithm was used by the authors to optimise the flow-obstruction's geometry and angular position. The optimised flow-obstruction was successful in reducing the magnitude of tonal noise attributable to the fans first blade passing frequency without increasing broadband noise.

Neuhierl and Felfoldi (2015) used a Lattice-Boltzmann method in combination with a rotating mesh. In so doing they were able to prediction both the transient blade-to-blade flow-field structures and the propagation of acoustic waves though the flow-field. The reported research focuses on predicting the installed acoustic performance of prototype fans embedded within a vehicle heating, ventilation and air conditioning system. The authors' objective in doing so was to reduce the number of physical prototypes needed when developing fans for application in a new vehicle heating, ventilation and air conditioning system. By using a Lattice-Boltzmann method in combination with a rotating mesh to model movement of the fan impeller the authors' were able predict the origin and propagation of the acoustic waves within the system. The authors concluded that their method effectively minimised the need for the testing of physical prototypes.

Le Goff *et al.* (2015) reviewed the research currently being undertaken within the air movement fan community, presenting the process by which numerical methods were applied to the prediction of engine cooling fan noise. The authors used Lattice Boltzmann methods for the automotive application, and then went on to apply their developed approach to predict the far-field noise of fans intended for heating, ventilation and air conditioning application. The Lattice Boltzmann method was able to provide an insight into the dominant noise sources when applied in both automotive and heating, ventilation and air conditioning applications.

5.8 TONAL NOISE MODELLING

Bouley *et al.* (2015) present a mode-matching technique for predicting the acoustic emissions from blade wakes as they impinge on fan outlet guide vanes. This wake-interaction noise is a dominant component of fan far-field noise and consequently its minimisation is of interest to fan designers. The authors' mode-matching approach utilises an 'unwrapped' representation of rotating components. By assuming continuity of pressure and axial velocity the authors' are able to predict the origin and propagation of acoustic waves. The magnitude and frequency of acoustic waves are directly calculated as a function of changing incidence angle onto outlet guide vanes. The authors conclude by considering the robustness of their mode-matching technique and the opportunities for its further development.

Zamiri *et al.* (2015) utilised an unsteady Reynolds-averaged Navier-Stokes numerical method for the spectral characterisation of a centrifugal fan. Centrifugal fans are used in a wide range of industrial applications, with their acoustic performance becoming an increasingly important aspect of their overall specification. The extant literature on centrifugal fan performance contains reports of the experimental characterisation on fan impeller-diffuser interactions and the resulting tonal noise. However, prediction of induced tonal noise remains challenging as a consequence of the three-dimensionality and turbulent flow-field features. In the reported research the authors validate their developed numerical method against experimental measurements, then go on to use it to optimise the fan design, and in so doing minimise fan far-field tonal noise.

Sanjose *et al.* (2015) utilised NASA 'active noise control fan' test facility to study fan tonal acoustic emissions and then used their experimental data set to validate an analytical noise prediction method. The authors used the aero-acoustic Lattice-Boltzmann method based code Powerflow to predict the unsteady flow-field though the fan and its direct noise radiation. The effect of near-field aerodynamic flow-field features on fan far-field noise is studied, and the sensitivity of far-field noise to fan geometry evaluated. The authors conclude that both the aero-acoustic code and their analytical model predict experimentally measured fan far-field noise with reasonable accuracy and provide an insight in its near-field aerodynamic origin.

5.9 INSTALLATION EFFECTS

Wu *et al.* (2015a) present a numerical method for predicting the acoustic performance of an axial fan when installed in an air conditioning unit. Air conditioning units are typically placed in close proximity to occupied buildings, and consequently their acoustic performance is a source of competitive advantage. In this paper the authors' study two types of residential air conditioning systems, analysing the performance of fourteen different units in total. They utilise a computational code and a vortex shedding acoustic model to predict both the fan installed aerodynamic performance and far-field noise. The authors conclude that predicted aerodynamic and acoustic performance are in reasonable agreement with measured performance, and characterise the acoustic implications of variations in air conditioning unit design.

Wu *et al.* (2015b) extend the research of Wu *et al.* (2015a), studying the effect of grill configuration on air conditioning unit acoustic emissions. The authors measured the far-field noise of an air conditioning unit without grills using particle image velocimetry. Measurements were then made with two existing grills and a new design of grill intended to reduce air conditioning far-field noise. The measurements confirmed that the new grill resulted in a reduced far-field noise level, with the authors concluding that the method used to design the new grill was effective.

Karekull *et al.* (2015) review the practical issues associated with the use of semi-empirical methods to predict the acoustic emissions form a heating, ventilation and air conditioning system intended for automotive application. The reported research reviews available semi-empirical scaling laws and their effectiveness when used to predict the far-field noise of heating, ventilation and air conditioning systems incorporating an embedded fan. Semi-empirical scaling laws are desirable during the initial design process as they avoid the need for a fully resolved unsteady simulation of the flow-field though both that heating, ventilation and air conditioning system and the fan embedded within it. The authors conclude that their computational approach and use of semi-empirical scaling laws is effective. It is able to account for both fan and system components of heating, ventilation and air conditioning system far-field noise.

Zenger *et al.* (2015) study the effect of in-flow turbulence on axial fan aero-acoustic performance when fitted with un-swept, forward and backward swept blades. The installed aero-acoustic performance of axial fans is influenced by in-flow turbulence that results from placing the fan downstream of heating, ventilation and air conditioning system components. The authors conclude by commenting on the impact of sweep on the fan far-field noise spectrum and how the impact of in-flow turbulence may be minimised by optimising blade sweep.

5.10 CURRENT ISSUES IN FAN NOISE

The papers focusing on heating, ventilation and air conditioning systems of cars collectively illustrate that minimising system noise requires a design engineer to optimise both system components and geometry of the fan embedded within the system. The research of Jung *et al.* (2015) illustrates that the optimisation of blade sweep can reduce significantly the far-field noise of a fan intended for automotive application. The research of Legros *et al.* (2015c) illustrates the effectiveness of an inverse design tool that facilitates the development of fan geometry intended to achieve a specific far-field noise target. The research of Legros *et al.* (2015b) presents a method for predicting fan far-field noise when the fan is embedded in an automotive heating, ventilation and air conditioning system. The research of Bennouna *et al.* (2015) illustrates a method for acoustically characterising each element of an automotive heating, ventilation and air conditioning systems that facilitates acoustic optimisation of that system.

The papers focusing on axial fan tip-leakage noise collectively illustrate that near-field aerodynamic features in the blade tip region constitute the origin of the dominant components within a fan far-field noise spectrum. The research of Zhu and Carolus (2015) illustrates that a numerical simulation may be used to characterise the far-field acoustic consequences of changes in both blade tip-to-casing gap size and fan operating point. The research of Allam and Åbom (2015) illustrates that the application and optimisation of micro-perforated plates and quarter-wave resonators in the blade tip region can effectively minimise fan far-field noise. The research of Lee and Bolton (2015) also studied the impact of micro-perforated plates when installed in the casing over fan blades. They concluded that the application of micro-perforated plates minimises fan far-field noise.

The papers focusing on signal processing for noise source localisation and characterisation collectively illustrate that the developed modelling techniques are able to predict with reasonable accuracy the far-field acoustic consequences of near-field noise sources. The research of Finez *et al.* (2015) illustrates the effectiveness of three methods for identifying the near-field noise sources responsible for fan far-field broadband noise, concluding that calculated broadband noise and spectrum were in reasonable agreement with measurements. The research of Horvath *et al.* (2015) illustrates that a range of near-field noise sources were responsible for fan on-axis far-field noise. The research of Sack *et al.* (2015) presents numerical strategies to predict and minimise aircraft air conditioning system acoustic emission with the agreement between predicted and measured noise levels being concluded to be reasonable. The research of Herold and Sarradj (2015) illustrates that a virtual microphone array can be used to identify the rotating noise sources associated with a rotating fan impeller. The research of Wang *et al.* (2015) illustrates that when two fans operate in series there are interaction based noise sources in addition to those associated with each fan. By modelling both individual and interaction noise sources the authors were able to minimise fan far-field noise.

The papers focusing on centrifugal fan noise collectively illustrate the challenges associated with predicting centrifugal fan acoustic emissions. The computational effort required to model the near-field flow-field with sufficient accuracy to predict centrifugal fan far-field noise is increasingly available to the air movement fan community, but remains formidable. The research of Iwase *et al.* (2015) illustrates that a large eddy simulation of the flow-field though a centrifugal fan may be used to predict with reasonable accuracy centrifugal fan broadband noise and spectrum. The research of Koyama *et al.* (2015) illustrates that the noise sources within a radial fan can be identified with sufficient accuracy to facilitate the optimisation of fan geometry to effectively minimise fan far-field noise. The research of Sasaki and Onomichi (2015) illustrates that it is possible to predict the far-field acoustic consequences associated with driving a centrifugal fan into rotating stall. The research of Hayashi *et al.* (2015) illustrates that centrifugal fan far-field noise changes significantly when the same impeller is installed in a casing or in an air conditioning unit. The authors were able to identify the near-field noise sources responsible for fan far-field noise in each application.

The papers focusing on the prediction of axial fan noise by hybrid methods collectively illustrate that useful predictions of fan far-field tonal and broadband noise are possible without attempting a direct numerical simulation of the fan flow-field. The research of Carolus *et al.* (2015) fosters the development of new steady and unsteady aerodynamic and aero-acoustic prediction methods by making available to the community a data set of a public domain fan aerodynamic and acoustic measurements. The research of Kucukcoskun *et al.* (2015) illustrates that a semi-analytical modelling technique may be used to characterise the far-field contribution of near-field broadband noise sources. The research of Chumakov *et al.* (2015b) illustrates that it is possible to undertake a blade-to-blade flow-field large eddy simulation, minimising the required computational effort by locally increasing computational mesh density in the near vicinity of the fan blade suction surface, pressure surface and trailing edge. The research of Becher *et al.* (2015) illustrates that the acoustic performance of a system may be optimised using a hybrid method that combines a numerical simulation of the flow-field with an empirical acoustic model. The research of Guedel and Robitu (2015) illustrates that it is possible to predict broadband noise using numerically predicted unsteady pressures as input to and empirical acoustic model. The research of Grasso *et al.* (2015) illustrates that a steady numerical simulation and semi-empirical acoustic model may be used to predict blade trailing edge noise. The research of Legros *et al.* (2015a) illustrates that following the experimental localisation of noise sources they were able to calculated the propagation of each noise source, both using an analytic approach and a computational approach.

The papers focusing on sound quality collectively illustrate that overall fan far-field broadband noise and spectrum do not fully characterise sound quality. The research of Schneider and Feldmann (2015) illustrates that human perception of sound quality is sensitive to tonal peaks breaking out of the broadband noise and the chaotic nature of far-field noise as a fan approached stall. The research of Minard *et al.* (2015) illustrates that fan noise must be minimised in hybrid or electric cars as it may be the dominant noise source due to the absence of noise sources associated with an internal combustion engine.

The papers focusing on Lattice Boltzmann methods collectively illustrate that they have advantages over other conventional computational fluid dynamics methods, especially in modelling the flow-field structures that constitute the near-field origin of fan far-field noise. The research of Kusano *et al.* (2015) illustrates that a simulation based on the Lattice Boltzmann method can predict fan far-field noise with accuracy similar to that of a detached eddy simulation. The research of Sturm *et al.* (2015) illustrates that measured fan far-field noise can be adversely affected by interaction noise associated with the test rig in which noise measurements are made. The research of Pain *et al.* (2015) illustrates that fan installed tonal noise may be minimised through the application and optimisation of a 'flow-obstruction'. The research of Neuhierl and Felfoldi (2015) illustrates that a Lattice-Boltzmann method in combination with a rotating mesh can be used to predict the origin and propagation of acoustic waves. The research of Le Goff *et al.* (2015) illustrates that a computational code incorporating a Lattice Boltzmann method can be used to optimise fan geometry, minimising fan far-field noise.

The papers focusing on tonal noise modelling collectively illustrate that modelling of tonal noise sources can facilitate the prediction of fan far-field tonal noise. The research of Bouley *et al.* (2015) illustrates that wake-interaction noise may be modelled using a mode-matching technique predict the origin and propagation of acoustic waves. The research of Zamiri *et al.* (2015) illustrates that centrifugal fan impeller-diffuser interactions may be modelled using an unsteady numerical method, and the resulting tonal noise predicted. The research of Sanjose *et al.* (2015) illustrates that experimental acoustic measurements may be used to validate fan broadband and tonal noise predictions made using an unsteady Lattice Boltzmann method based numerical simulation. The numerical simulation is accurate when it models the complete fan-stage flow-field and incorporates an analytical model to account for duct propergation.

The papers focusing on installation effects collectively illustrate that fan far-field broadband and tonal nose is significantly influenced by the system within which a fan is embedded. Therefore methods for predicting installed fan noise are a priority for the air movement fan community. The research of Wu *et al.* (2015a) illustrates that the acoustic characteristics of a fan installed in an air conditioning system may be predicted with reasonable accuracy using a numerical method based on a vortex shedding acoustic model. The research of Wu *et al.* (2015b) illustrates that the far-field noise of an air conditioning system may be minimised through the optimisation of air conditioning system grills. The research of Karekull *et al.* (2015) illustrates that semi-empirical scaling laws may be used during the initial design phase of an air conditioning system, avoiding the need for the early use of large scale numerical simulations. The research of Zenger *et al.* (2015) illustrates that in-flow turbulence generated by upstream air conditioning system components has a primary impact on fan far-field noise. The authors demonstrate that in-flow turbulence induced noise may be minimised though an optimisation of fan blade sweep.

6.0 CURRENT ISSUES FACING THE AIR MOVEMENT FAN COMMUNITY

The air movement fan community is addressing issues associated with the application of computational methods to fan design, fan technology and fan noise. The action being taken is within the context of current regulatory environment. The issues are summarised, and then action the community has taken in response is discussed. Further, the papers presented at Fan 2015 are in many cases associated with on-going research programs. It has therefore been possible to comment on the action that the community in the process of taking and is planning to undertake in response to the forthcoming regulatory environment.

6.1 COMPUTATIONAL METHODS

Researchers studying the application of computational methods to air movement fan design 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.

The papers focusing on optimisation methods for axial fans collectively illustrate that it is possible to use computational methods to optimise fan performance. 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 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 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.

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). The minimum FMEG levels were increased again on the 1st January 2015, eliminating additional low efficiency fans from the European market. By the end of 2015 Mr Gonzalez Álvarez 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.

6.2 FAN TECHNOLOGY

Researchers developing new fan technology have focused their effort into five areas of endeavour:

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

The papers focusing on measurement and test collectively illustrate that innovation in instrumentation and experimental measurement techniques is both possible and able to make a contribution to the community. As computational methods become more sophisticated, the need increases for experimental datasets to validate them. The papers focusing on electric motors collectively illustrate that the design and integration of electric motors into air movement fans is associated with a range of challenges. These challenges can result in sub-optimal motor design for the application, and in extreme cases in-service failure of the motor or fan into which the motor is integrated or driving. The papers focusing on fan performance collectively illustrate that performance prediction and the optimisation of fan geometry to maximise performance remain an issue for the air movement fan community. The papers focusing on fan design methods collectively illustrate that design methods can be extended to facilitate the optimisation of fan geometry for operating at off-design conditions. The papers focusing on fan efficiency collectively illustrate that current and forthcoming regulatory targets for minimum fan efficiency are driving the air movement fan community to develop methods for improving fan efficiency.

In his key-note lecture Mr Godichon observed that 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 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. 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. 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 far-field broadband noise and spectrum. However, the computational effort required is high and remains beyond that available within the air movement fan community. Mr Godichon concluded by observing that the primary advances in fan technology over the last five decades may be attributed to the increasing use of numerical methods.

6.3 FAN NOISE

Researchers studying the modelling and prediction of fan noise have focused their effort into nine areas of endeavour:

- heating, ventilation and air conditioning of cars;
- tip leakage noise of axial fans;
- signal processing for noise source localisation and characterisation;
- noise of centrifugal fans;

- prediction of axial fan noise by hybrid method;
- sound quality;
- Lattice Boltzmann methods;
- tonal noise modelling;
- installation effects.

The papers focusing on heating, ventilation and air conditioning systems of cars collectively illustrate that minimising system noise requires a design engineer to optimise both system components and geometry of the fan embedded within the system. The papers focusing on axial fan tip-leakage noise collectively illustrate that near-field aerodynamic features in the blade tip region constitute the origin of dominant components within a fans far-field noise spectrum. The papers focusing on signal processing for noise source localisation and characterisation collectively illustrate that the developed modelling techniques are able to predict with reasonable accuracy the far-field acoustic consequences of near-field noise sources. The papers focusing on centrifugal fan noise collectively illustrate the challenges associated with predicting centrifugal fan acoustic emissions. The computational effort required to model the near-field flow-field with sufficient accuracy to predict centrifugal fan far-field noise is increasingly available to the air movement fan community, but remains formidable.

The papers focusing on the prediction of axial fan noise by hybrid methods collectively illustrate that useful predictions of fan far-field broadband and tonal noise are possible without attempting a direct numerical simulation of the fan flow-field. The papers focusing on sound quality collectively illustrate that overall fan far-field broadband noise and spectrum do not fully characterise sound quality. The papers focusing on Lattice Boltzmann methods collectively illustrate that they have advantages over other conventional computational fluid dynamics methods, especially in modelling the flow-field structures that constitute the near-field origin of fan far-field noise. The papers focusing on tonal noise modelling collectively illustrate that modelling of tonal noise sources can facilitate the prediction of fan far-field tonal noise. The papers focusing on installation effects collectively illustrate that fan far-field broadband and tonal nose is significantly influenced by the system within which a fan is embedded. Therefore methods for predicting installed fan noise are a priority for the air movement fan community.

In his key-note lecture Professor Moreau observed that a key challenge facing design engineers when attempting to predict fan noise is that the flow-field is characterised by turbulence that is classically difficult to predict. Analytical methods for predicting fan noise are therefore 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 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. However, very large eddy simulations and numerical simulations based on Lattice-Boltzmann methods provide an alternative and effective was to simulate fan aero-acoustic performance at moderate cost.

Consequently the use of Reynolds-averaged Navier-Stokes 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 Reynolds-averaged Navier-Stokes simulation.

6.4 DISCUSSION

There is an acceptance within the air movement fan community that minimum fan and motor efficiencies are regulated, and that minimum requirements will increase over time. The general consensus amongst those attending Fan 2015 was that the practical consequence of regulation has been positive. More efficient fans are invariably more expensive fans, and consequently an effect of regulation has been to increase the value of the air movement fans sold. Although those who purchase them are burdened with having to pay for a more expensive product in the short term, in the medium and long term they also benefit. To a first order one may assume that a three percent increase in fan efficiency will reduce the cost of electricity used to drive the fan by more than the capital cost of the fan over a ten year period. From this we may infer that the only negative consequence associated with regulation is the disruption associated with forcing change upon a mature industry.

The above characterisation of the air movement fan communities response to regulation is within the context of existing fan technology being adequate. The recently introduced 2015 minimum fan and motors efficiency grades have resulted in the some market segments requiring fan efficiencies that are not easily achieved with existing fan technology. As a direct consequence the air movement fan community has responded by increasing the rate of product development. This product development effort has not necessarily required the application of new technology. Many air movement fans have changed little since their original design thirty or even forty years ago. Development therefore constitutes no more than the application of current finite element analysis and computational fluid dynamic numerical methods. By optimising geometry efficiency can be improved sufficiently to enable a manufacture to meet both current and forthcoming regulatory requirements. Although a viable response when a single product range required development, forthcoming regulatory requirements are increasingly challenging. Consequently an increasing proportion of current product ranges require development, with the sheer volume of development work becoming potentially overwhelming. There is therefore an increasing acceptance of the need for today's semi-empirical development tools to be replaced by computationally based methods. The purpose in doing so is to characterise and optimise fan geometry an order or magnitude more quickly than has been the historic norm within the air movement fan community.

The Fan 2015 conference papers each constitute an individual contribution to knowledge. Collectively they demonstrate that progress in the development of fan technology is directly linked to increasing computer power. Numerical methods for mechanical analysis became established in the air movement fan community during the 1980's, despite the limited available computer power. Commercial computational methods modelling the flow-field physics correctly became available around the year 2000; however adoption was limited as a consequence of a lack of available computer power. By 2010 the available commercial computational methods and computer power were sufficient to be used as a routine part of the design process by air movement fan designers. However, adoption remained limited as a consequence an air movement fan market driven by cost and lead time. Despite the forthcoming regulatory environment, fan efficiency was not perceived as a priority.

Around 2010 those members of the air movement fan community who were actively involved in the writing of codes and standards became aware that the European Union was in the process of regulating minimum allowable fan efficiency. As minimum allowable fan efficiency regulation came into effect in 2013 the need to increase the speed at which new products could be developed was recognised. In effect products developed over decades using traditional empirical and semi-empirical methods had to be collectively replaced an order of magnitude more quickly than they had been originally developed. This realisation resulted in the progressive adoption of computational methods for predicting fan performance. This adoption was at least partly driven by an assumption that the minimum allowable fan and motor efficiency levels introduced on January 1st 2015 would increase further. Thus there was an acceptance of a need to continue to improve fan efficiency and hence a need to continue the process of embedding computational fluid dynamics computational methods into the fan design process.

The above constitutes an essentially European perspective. Those US air movement fan manufactures that are choosing to development their portfolio of products do so in expectation that fan efficiency will become a source of competitive advantage. When the Department of Energy minimum allowable fan efficiency levels come into effect in 2020, those manufactures that have developed their product ranges and can comply will have an advantage over those who have not. However the blunt truth is that today within the US market competitive advantage is driven by product cost and lead time. As energy costs are low in the US, efficiency is not a source of competitive advantage and therefore air movement fan efficiencies are typically low.

Both within Europe and the US those manufacturers who are developing their products are finding that the act of bringing multiple new products to market simultaneously is challenging. Both air and acoustic performance data is needed for new products and the increasing rate with which products are being brought to market has the potential to become overwhelming. The product development process itself therefore requires developing, shifting away from the physical testing of prototypes. Air movement fan manufactures are therefore increasingly driven to use computational methods, not to improve fan efficiency, but simply to generate the necessary air and acoustic performance data over each products complete operating envelope.

Computational fluid dynamics computational methods are classically applied to the design of more efficient fan designs. However they can be applied as ‘virtual laboratories’ to predict fan performance as it would be measured in a physical laboratory. This enables the air performance of multiple fan configurations to be predicted an order of magnitude more rapidly than would be possible by building and testing physical prototypes of pre-production fans. The application of computational methods is therefore a consequence of different drivers within Europe and the US. In Europe the primary driver is the development of more efficient fans in anticipation of more stringent minimum fan efficiency requirements. In the US anticipated minimum fan efficiency levels are low enough that the focus is on improving the efficiency of a broad range of products. Despite the different drivers, both European and US fan manufactures are increasingly adopting computational fluid dynamics computational methods for predicting air performance.

In addition to air performance, it is necessary to know the acoustic performance of newly developed air movement fans. At a developmental level the acoustic implications of design choices when developing new products should be considered. When characterising the performance of a new product range it is necessary to know the acoustic performance of every product over its entire operating envelope. Historically is has been accepted within the air movement fan community that acoustic performance will be measured when testing a physical prototype. However as the rate at which new products are brought to market increases, it is simply not possible to conduct the necessary volume of physical tests in the available time.

There are empirical acoustic models developed in the 1960’s are remarkably effective at predicting fan broadband noise and spectrum. However, they have their limitations and that is why air movement fan designers continue to rely on physical testing. The Fan 2015 conference included papers focused on the use of computational methods for predicting fan noise. They focus on modelling the flow-field physics and the use of computational models requiring computer power significantly beyond that available within the air movement community. However, the Fan 2015 conference papers also include examples of semi-empirical and hybrid computational methods that predict acoustic performance with lower computational effort. Although involving significant simplifying assumptions, these computational methods never the less are able to predict fan acoustic performance with reasonable accuracy.

The air movement fan community has not begun to seriously consider the use of computational methods to predict fan acoustic performance. However, the adoption of computational methods within the air movement fan community has followed a pattern over the last four decades. Initially computational methods predicting mechanical stress were adopted in the 1970’s to help avoid in service failures. The use of computational methods to predict mechanical stress became routine within the air moment fan community during the 1990’s. Commercially available computational methods predicting air performance were first used in the 1980’s. However, they did not model the physical equations accurately until about the year 2000. Although there is widespread acceptance within the air movement fan community that they are an inevitable part of any new product development process, they are not yet embed in current product development processes.

Computational methods for predicting fan acoustic performance are not part of air movement fan manufacturers’ product development process. However, they are routinely used within the academic community working with the air movement fan community. Within this academic community the use of computational methods to predict fan noise is a primary research area. Predicting fan noise using computational methods is today a capability that the majority of air movement fan manufactures are not aware exists. However, the speed with which computational methods have been applied to mechanical and aerodynamic analysis indicates that they will become part of their product development processes within the next decade.

CONCLUSIONS

The air movement fan community is addressing issues associated with the application of computational methods to fan design, fan technology and fan noise. This review of the papers presented at the conference Fan 2015 has identified the issues associated with each, and summarised the collective contribution of knowledge.

A review of the papers presented at the conference Fan 2015 plus the three conference key-note speeches has clarified that there is within the air movement community a broad based acceptance that for the first time the air movement fan community is being regulated. The industry response to the minimum allowable fan and motor efficiency grades that became legally binding within Europe on 1 January 2013 was minimal. Alternative existing products could, and in most cases were selected that were physically larger, running at a lower speed and therefore closer to the fans peak efficiency operating point. This passive approach was less successful when attempting to select products that complied with the 1 January 2015 minimum allowable fan and motor efficiency grades. These grades were high enough to require some product development, with computational methods that could predict air performance starting to gain traction within the community. This adoption was driven partly in response to historical empirical and semi-empirical methods reaching the limit of their capability. It was also driven partly in response to a need to predict air performance more quickly than was possible by building and testing physical prototypes.

Within Europe there is an acceptance that minimum allowable fan and motor efficiency grades will increase again on 1 January 2020. Within the USA there is an acceptance that minimum fan efficiency levels will be regulated by 2020. Although the response to forthcoming regulatory requirements in Europe and the USA is different, in both geographic regions there is a rising awareness that product ranges developed over decades will need to be re-developed in less than one decade. Within the air movement fan community this realisation is driving the development of already adopted computational methods for predicting mechanical stress levels, mode shapes and natural frequencies. It is also driving the adoption of computational methods for predicting air performance. Within the academic community working with the air movement community it is driving the development of computational methods that can predict broadband far-field noise and spectrum. Although not yet ready for adoption by air movement fan manufacturers, the pressure to reduce the time taken to bring new products to market will drive their incorporation into product development processes.

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