ISABE-2009-1187

Comparative Performance Evaluation of a Multistage Axial Fan Assembly

Alexandros Terzis, Konstantinos Kyprianidis, Pavlos Zachos, Anestis I. Kalfas* et al**

Cranfield University
Department of Power and Propulsion
MK43 0AL, Bedfordshire, UK

** Aristotle University of Thessaloniki*
Department of Mechanical Engineering
GR-54124 Thessaloniki, Greece

ABSTRACT

Small fans which are primarily axial machines induce the air movement of a relatively large mass flow within comparatively low velocities for reasons of thermal management. In the present investigation six axial fans of the same type were assessed for their structural (inactivity), geometrical and dynamic similarity. The results indicated that the fans including the stators and the rotors were operationally and dynamically similar. A series of experiments was conducted for a single stage, 2-stage and 3-stage fan configurations. The experimental data were used for the derivation of a linear algebraic model, as well as for calibrating a stage stacking model developed by Cranfield University for predicting the overall performance of multi-stage axial flow machines. The comparison between the computed values and the experimental data indicated very good agreement in the entire range of speed lines. The algebraic model can be used with high confidence for predicting the fan performance for rotational speeds where experimental data are not available. The validated stage stacking model can be used for predicting the performance of multi-stage low-velocity axial fans when experimental data are only available for a single stage.

NOMENCLATURE

Symbols

a	Constant
b	Constant
D	Diameter
m [kg/s]	Mass flow rate
N	Non-dimensional rotational speed
V [m/s]	Velocity
ΔP [Pa]	Pressure rise

Subscripts

i	Fan number
ref	Reference conditions
α	Axial direction

INTRODUCTION

Fan selection is usually concerned with its characteristic curve which defines a relation between pressure and mass-flow. For incompressible flow due to the low developed pressure rise, the characteristic curve of a small axial fan, for standard atmospheric conditions, can be expressed as pressure difference against mass flow rare at a given rotational speed. The selection of a particular fan design depends on its application and has been discussed previously [1-2].

The most common technique used in order to understand the thermal capabilities and the performance of a fan impeller is well known as 'constant speed stage performance' and the main apparatus of this configuration has been described widely previously [3-6]. Fan operation at all conditions can be simulated with variation of mass flow using a conical throttle valve in the exit plane. Pressure will increase continuously with reducing mass flow until the surge point is

Pericles Pilidis

Copyright ©2009 by Cranfield University
Published by the American Institute of Aeronautics and Astronautics, Inc., with permission

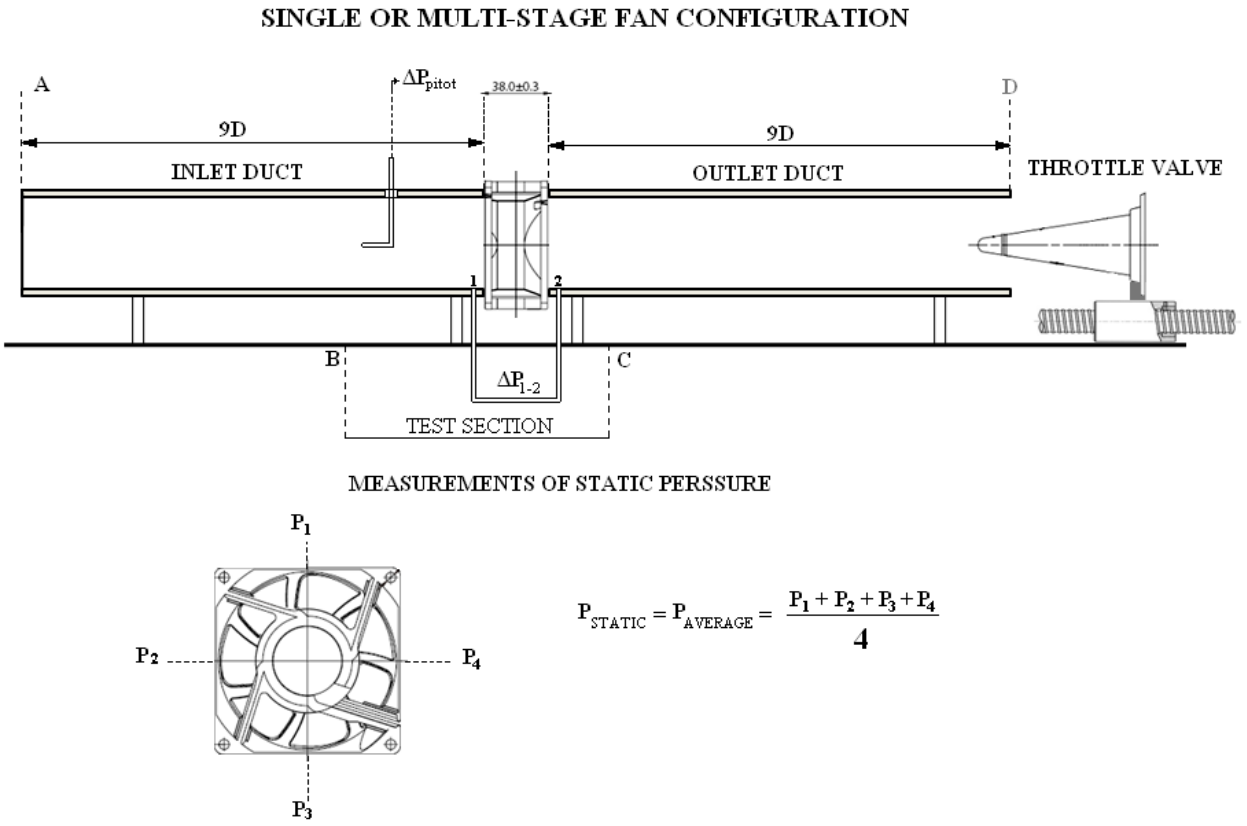


Figure 1 *Experimental Setup and Measurement Stations*

reached; the diffusing blade passage will no longer be able to handle the positive pressure gradient, hence resulting in flow separation (and increased pressure losses). This in turn will cause a reduction to the developed pressure rise along the fan blades. Several attempts have been made in order to delay the surging conditions of a fan by fluid injection at the tip of the fan casing[6-7]. Many researchers have realized various experiments in order to obtain the performance of a single[3,8-10] or multi-stage axial fan configurations[11-12]. Their results indicated a linear relation between pressure rise and mass flow at a given rotational speed. However, it has been pointed out that the linearity was pulling down near the surge point or when the rotational speed exceeded a critical value, typically of 75% to 80% of the maximum speed. The main cause for this situation is the compressible character of the flow when approaching choked conditions at high mass flow rates. Furthermore, it has been observed, using non-dimensional performance parameters, that the spread of various experimental data, with respect to the speed lines, can be attributed to compressibility effects.

Since axial flow fans and compressors are important parts of gas turbines many attempts have been made in order to model the performance and the behaviour of multi-axial machines. The stage stacking technique is a simple and accurate method of modelling axial fans and compressors and has been used widely by various authors [13-16]. A similar simulation method has been developed at Cranfield University and the main objective of the present investigation is the validation of the numerical performance model and its further calibration with respect to the experimental data.

EXPERIMENTAL SETUP

Facility

The experimental facility used in the present investigation is illustrated in Figure 1. The set up consists of long upstream and downstream ducts of constant area, the test section and the

Copyright ©2009 by Cranfield University
Published by the American Institute of Aeronautics and Astronautics, Inc., with permission

throttle valve. The main advantage of this configuration is that the number of stages of a multi-stage axial flow fan that can be measured is not limited. Nevertheless, attention should be paid in the collimation of the test section especially when a large number of fan stages is to be tested The entrance length, which is the upstream duct length, is approximately 9 diameters long (9D), where D is the diameter of the fan. This configuration allows the flow velocity profile in the duct to be fully developed after the obstruction in the entrance lip and possible separation of the flow due to the absence of a bell mouthed inlet. In addition, since the aspect ratio of the cone throttle was reasonable high, a similar configuration has been also used for the downstream duct in order to regularize the distribution of the flow lines. It should be noted that although pressure losses increase when long ducts are utilized (18D), the high quality of the duct surfaces did allow for the assumption of a negligible friction coefficient between the tube surface and the fluid.

The experimental set up and the measurement planes are illustrated in Figure 1. Velocity is measured using a Pitot-Static tube in plane B for evaluating the mass flow rate. The static pressure is measured upstream and downstream of the fan assembly at four different, radially spaced points, as illustrated in figure 1b. Since the static pressure profile is constant, an average value of the static pressure is taken into consideration as a more accurate measurement for the calculation of the total pressure rise. Finally, the rotor rotational speed was measured using a digital infrared laser tachometer; measurement accuracy was within ±0.05%.

Axial Flow Fans

The axial flow fans used in the present investigation are illustrated in Figure 2 while its characteristics are summarized in Table 1. The blade rows consist of 7 rotor blades followed by 9 stator blades of the same hub to tip ratio. The number of stators is slightly higher than rotors in order to completely remove the swirl velocity at the end of the rotational part of the fan. As a result the velocity vector at the exit of the test section consists only of the axial velocity term V_a. Subsequently, by utilizing the energy equation - and making the assumption that pressure losses in the ducts as well as the swirl velocity term after the rotor are negligible - the total pressure rise in the test section will equal the static pressure difference just upstream and downstream of the fan. The range of the rotational speed measured in the present work was from 50% to 100% of the design speed, with steps of 8.33%.

Experimental Procedure

Fan speed lines can be measured by varying the mass flow rate using the conical throttle valve inthe exit plane of the test facility, as shown in Figure 1. The reduction of the exit plane area by axially displacing the conical throttle reduces the mass flow rates and increases the pressure difference at a given rotational speed, until surge occurs. The movement of the conical throttle valve was carried out in steps of 15mm to 5mm, with a gradual step reduction as the surge point in the fan map was approached. Apart from measuring the fan performance in the unstalled region, some measurements have also been carried out in the stalled region in order to investigate the performance behavior of the fan at stall conditions. Twelve sets of measurement data were collected for each speed line in order to derive the performance characteristic of the fan.

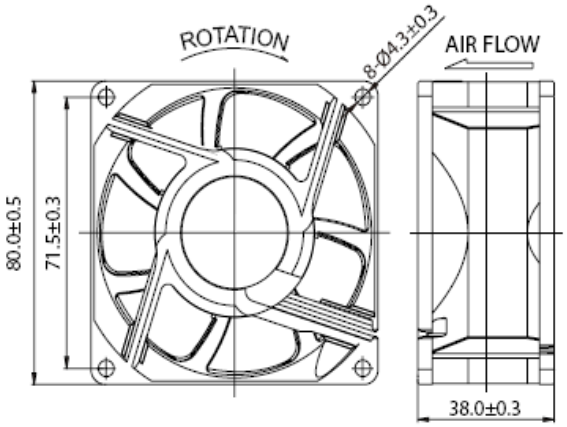


Figure 1 *Axial flow fan*

Fan type	Axial Flow Fan
Rotational speed [max]	6000 rpm
Inlet hub to tip ratio	0.4
Absolute air inlet angle	0^o
Outlet angle	0^o
Number of Stages	1-3
Number of Rotors	7
Number of Stators	9

Table 1 *Axial Flow Fan Characteristics*

Copyright ©2009 by Cranfield University
Published by the American Institute of Aeronautics and Astronautics, Inc., with permission

Algebraic Model

In the present investigation six fans of the same type were assessed for their structural (inactivity), geometrical and dynamic similarity. The experimental results indicated that the axial flow fans, including the rotors and the stators were operationally and dynamically similar. Due to their similarity a single fan map can be used for representing the performance of all the fans measured. The extraction of this unique fan map is based on the weighted average method; a fan with a higher mass flow at a given throttle point, and rotational speed, has a greater contribution to the final value of pressure rise. The calculation of the average pressure and average mass flow rate of the six fans at a given cone throttle point, is based on the following equations:

$$\Delta P_i = \frac{\sum_1^6 \Delta P_i m_i}{\sum_1^6 m_i}$$

$$m_i = \frac{\sum_1^6 m_i}{6}$$

Each one of these points (ΔP and m) represents a single point in the final fan map. These values have been non-dimensionalised using a reference operating point.

In order to obtain a unique fan map, an attempt was made to correlate the unstalled region of this single stage fan map using a linear algebraic model described by the following equation:

$$\Delta P = am + b$$

where a and b are constants and depend on the fan diameter D and the geometry of the blades.

The variation of constants a and b with rotational speed is illustrated in Figure 3. The constant a, is essentially the inclination of the characteristic curve at a given rotational speed and serves as an index of compressibility. For a completely incompressible flow there is no variation in the value of constant a with rotational speed, as illustrated in Figure 3. Constant b, on the other hand represents the height of the characteristic curve from the mass-flow axis of the fan map. The experimental data indicate that constant b correlates well with the square of the fan rotational speed:

$$b = f(N^2)$$

The mass flow range is determined from the surge line and the maximum mass flow rate line (no throttle valve), as illustrated in Figure 4.

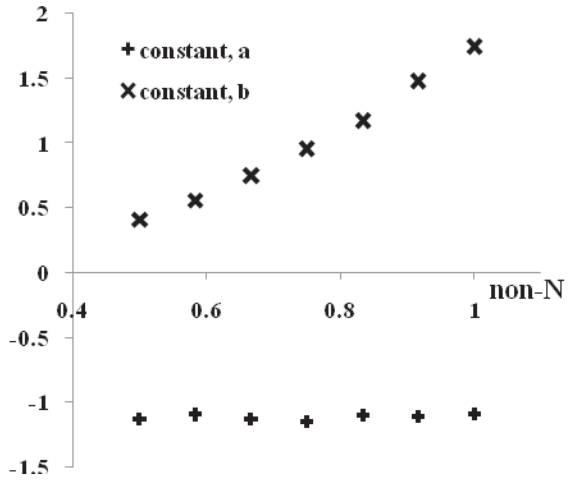


Figure 2 *Variation of algebraic model constants a and b with rotational speed*

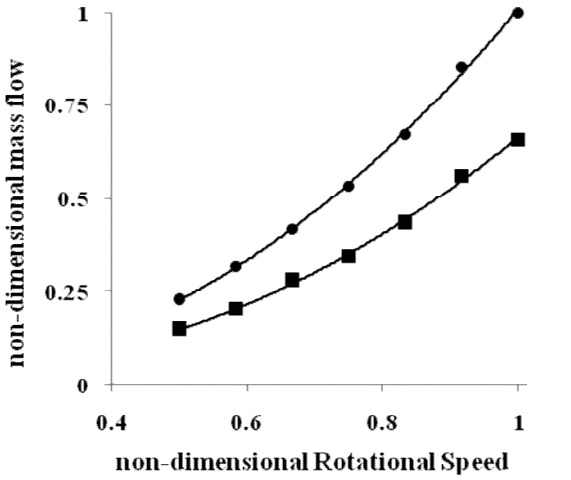


Figure 3 *Minimum and maximum measured mass flow rate against rotational speed*

Copyright ©2009 by Cranfield University
Published by the American Institute of Aeronautics and Astronautics, Inc., with permission

RESULTS

Experimental Data and Algebraic Model

The similarity of the six single stage axial flow fans is illustrated in Figure 5 and Figure 6. The increase in pressure rise is proportional to the square of the rotational speed. The experimental results for the six axial flow fans are very close, indicating the aerodynamic similarity of the blades. Moreover, it can been seen in Figure 6 that the increase in static pressure through the rotor and the stator is greater at higher rotational speeds when the throttle valve is moving linearly in the internal of the downstream tube.

Also of interest is when as reference conditions for non-dimensionality are used the . It can be observed that in the entire range of rotational speeds the surge region of the fan is reached at a constant ratio of exhaust area to inlet area A_{ex}/A_{in}. As described earlier, the area ratio can be varied by axially displacing of conical throttle valve – it will decrease with increasing throttle distance. In addition, it is evident that the surge of the fan, in the entire range of rotational speeds, is achieved when the exhaust area reaches 38-43% of the inlet area. Furthermore, the flow is completely incompressible since the non-dimensional characteristic curves of these fans, at various speed lines, coincide. It is evident from Figure 7 that there is no variation in the slope of the curves with respect to the speed lines.

The results indicate that the fans, including both stators and rotors, were operationally and dynamically similar and subsequently a unique fan map has been extracted in order to represent the performance behavior of all the fans. This unique fan map is illustrated in Figure 8. It can be observed that the operation range of the fan is increasing with rotational speed.

A comparison of the algebraic model with the experimentally derived fan map is illustrated in Figure 9. A good agreement between the algebraic model and the weighted average experimental data can be observed. Therefore, the algebraic model can be used with high confidence for predicting speed lines for which experimentally data are not available, as illustrated in Figure 9 for 60% and 80% of the maximum rotational speed.

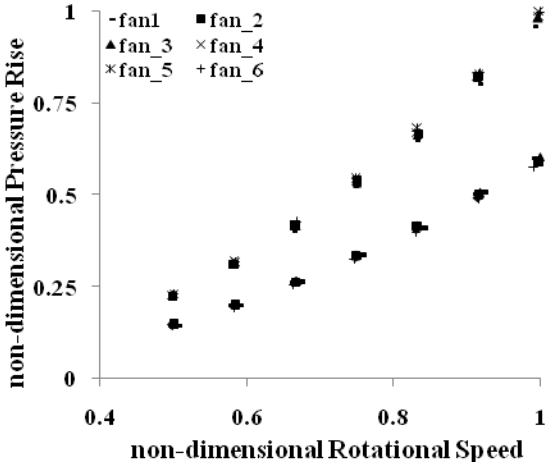


Figure 4 *Minimum and maximum measured pressure rise against rotational speed*

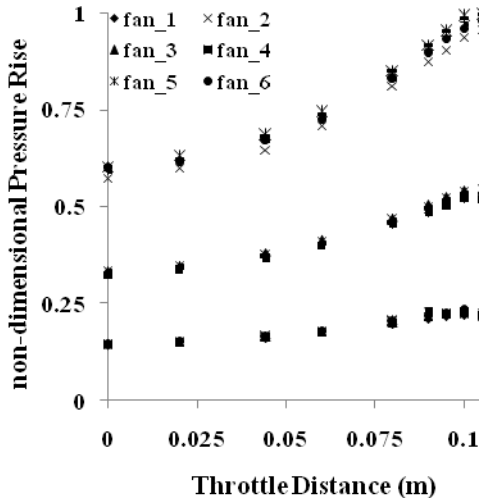


Figure 5 *Measured pressure rise against throttle distance*

Copyright ©2009 by Cranfield University
Published by the American Institute of Aeronautics and Astronautics, Inc., with permission

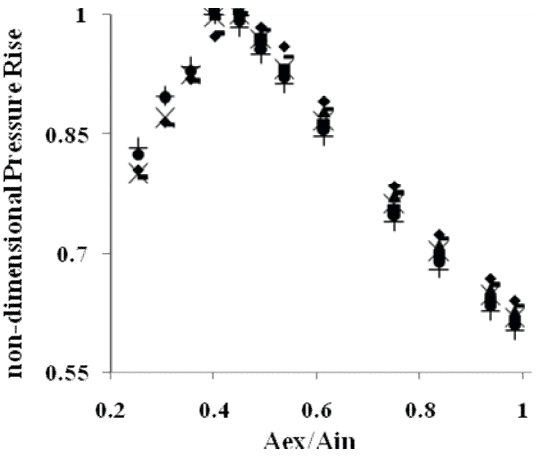
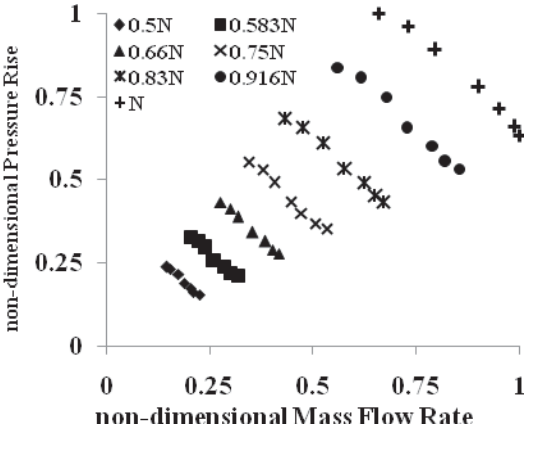


Figure 6 *Measured pressure rise against area ratio for various rotational speed lines*



Fi

Figure 7 *Experimentally derived map for a single stage fan*

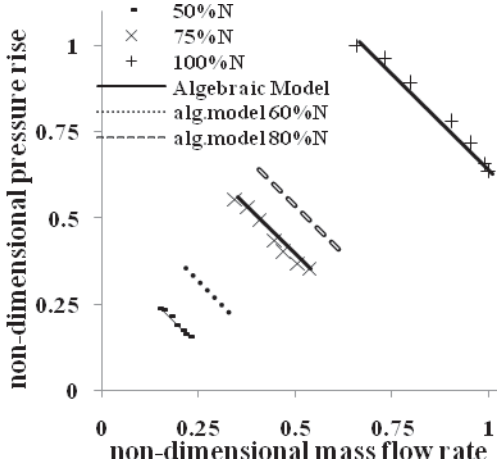


Figure 8 *Comparison of algebraic model with experimental results for a single stage fan*

Experimental Data and Stage Stacking Model

The experimentally derived single stage fan map was also used by the stage stacking method for predicting the performance of a multi-stage fan assembly. The validation of this numerical fan performance model was based upon experimental data of 2-stage and 3-stage fan configurations.The overall performance of the multi-stage axial fan, as computed by the stage stacking model, is compared with experimental measurements in Figure 10 and Figure 11; these measurements were conducted in the same manner as with the single stage fan configuration.

The 2-stage numerical performance model is compared with the experimental data in Figure 11. A good agreement is observed between the computed values and the experimental results over the entire rotational speeds (50%N, 75%N and 100%N). It should be noted that the accuracy is slightly higher at lower rotational speeds.

The 3-stage numerical performance model is compared with the experimental data in Figure 12. A good agreement between the computed values and the experimental data is also observed for the entire range of rotational speeds. It should again be noted that deviations are at lower speed lines. Finally, it can be observed that the inclination of the speed lines is slightly higher than in the 2-stage fan configuration.

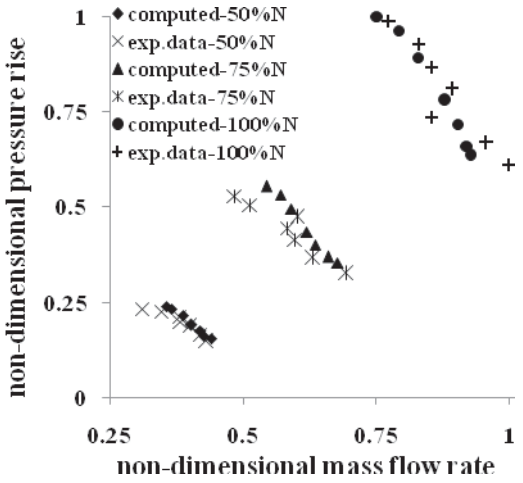


Figure 9 *Comparison of computed values with experimental results for a 2-stage fan*

Copyright ©2009 by Cranfield University
Published by the American Institute of Aeronautics and Astronautics, Inc., with permission

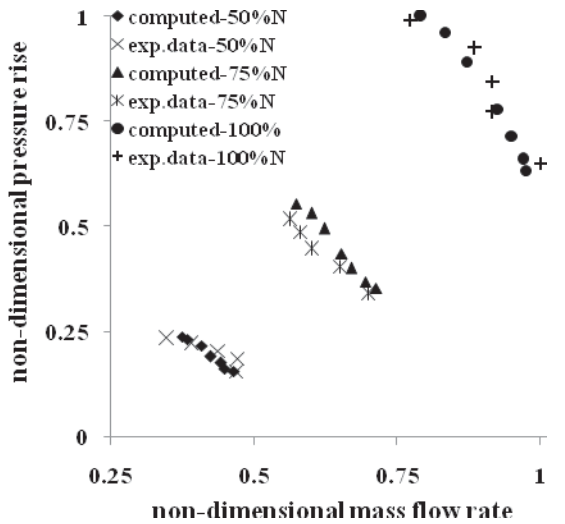


Figure 10 *Comparison of computed values with experimental results for a 3-stage fan*

UNCERTAINTY ANALYSIS

The knowledge of the accuracy of the test results and the simulation method is of extreme importance. Deviation or uncertainty analysis is used widely for the evaluation of the validity of a numerical model compared with experimental data.

Uncertainty analysis results can often be presented with simple deviation charts where the computed values of a particular parameter are plotted against the experimental results on the vertical and horizontal axis respectively. The ideal case is when the two values are equal, which can be demonstrated graphically for the entire spread of values by a straight line defined by the equation $y=x$. Low uncertainty will then be indicated if all points in the graph are sufficiently close to this line.

A deviation analysis of the computed values against experimental results for the algebraic model (single stage fan configuration) is demonstrated in Figure 12 and Figure 13. In the first figure, the calculated mass flow rate is compared against experimental data, while in the latter figure the accuracy of the algebraic model is essentially illustrated in terms of pressure rise. In both cases uncertainty when using the algebraic model is within 5% i.e. the linear algebraic model holds well for an incompressible flow.

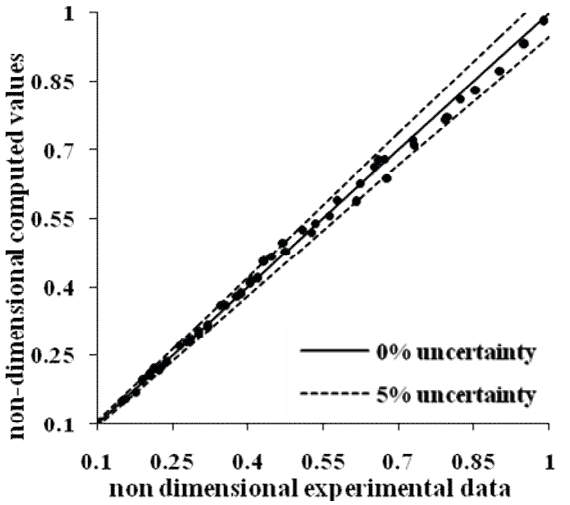


Figure 11 *Comparison of computed mass flow values, for a fixed pressure rise, with experimental results – Algebraic model for single stage fan*

A deviation analysis of the computed values against experimental results for the stage stacking model is demonstrated in Figure 14 and Figure 15. In the first figure, the calculated mass flow rate is compared against experimental data for a 2-stage fan, while in the latter the uncertainty for a 3-stage fan is illustrated. For the 3-stage fan deviations are marginally higher than in the 2-stage fan, but even so, induced uncertainty when using the stage stacking model is still within 10% for both configurations. This can be considered satisfactorily good for modelling the performance of multi-stage low-velocity axial fans when experimental data are only available for a single stage.

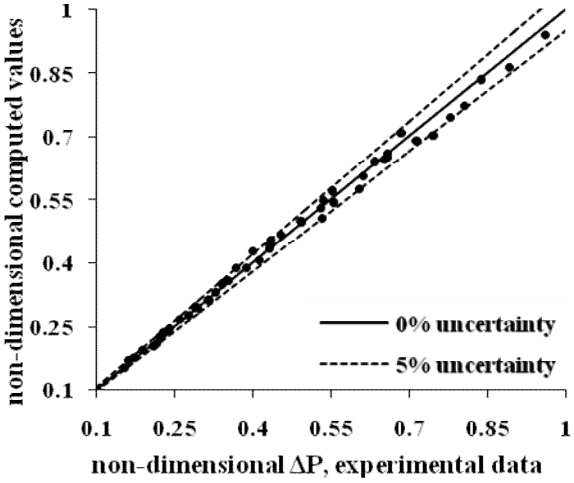


Figure 12 *Comparison of computed pressure rise values, for a fixed mass flow, with experimental results – Algebraic model - Single stage fan*

Copyright ©2009 by Cranfield University
Published by the American Institute of Aeronautics and Astronautics, Inc., with permission

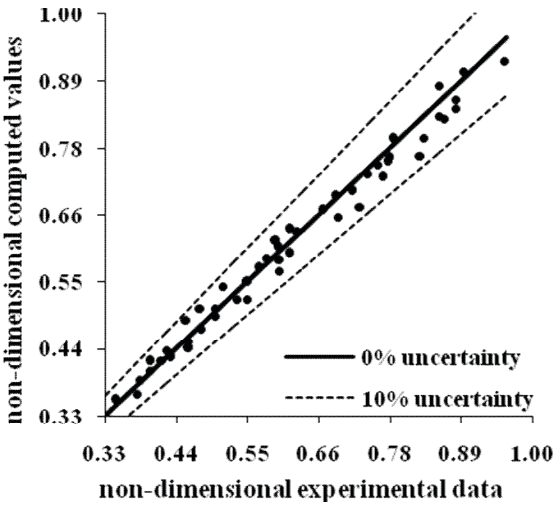


Figure 13 *Comparison of computed mass flow values, for a fixed pressure rise, with experimental results – Stage stacking model for 2-stage fan*

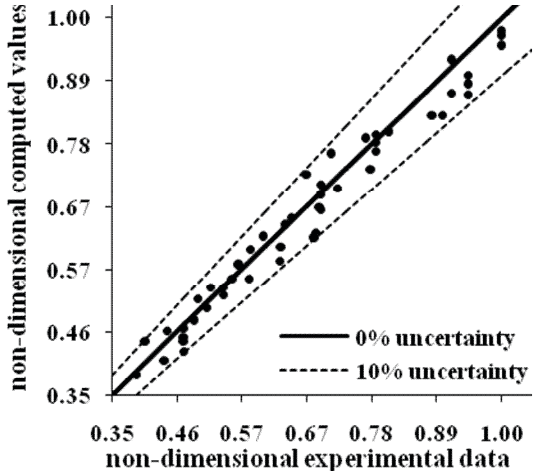


Figure 14 *Comparison of computed mass flow values, for a fixed pressure rise, with experimental results – Stage stacking model for 3-stage fan*

CONCLUSIONS

In the present investigation experiments were carried out in order to obtain the performance characteristics of a single, 2-stage and 3-stage fan configurations. The experimental data were used for the derivation of a linear algebraic model, as well as for calibrating a stage stacking model developed by Cranfield University for predicting the overall performance of multi-stage axial flow machines. The comparison between the computed values and the experimental data indicate very good agreement in the entire range of speed lines. The algebraic model can be used with high confidence for predicting the fan performance for rotational speeds where experimental data are not available. The validated stage stacking model can be used for predicting the performance of multi-stage low-velocity axial fans when experimental data are only available for a single stage.

ACKNOWLEDGMENTS

The authors would like to acknowledge Dr. Ken W. Ramsden and Pavlos K. Zachos for their contribution to improve the overall quality and clarity of the paper. The authors are also grateful to Mr. Konstantinos Zachos for the support and structure of electronic equipment.

REFERENCES

1.Osborn, W. C. (1967). *Fans*. Oxford: Pergammon Press.

2.Wallis, A. R. (1983). *Axial Flow Fans and Ducts.* John Willey & Sons.

3.Bodgonof, S. M., & Herring, J. L. (1946). *Performance of Axial-Flow Fan and compressor.* NACA TN-1201.

4.Institution, B. S. (1980). *Fans for General Purposes. Methods of Testing Performance , part 1* . BS 848.

5.Mousley, L. J., Randall, M., Hartson, R. L., Houghton, C. L., & Randie, D. G. (1987). *Facilities for Measuring Fan Performance*. AFRC.

6.Bhaskar R., Manish C., K. V. Kaundinya (2005) *Experimental Study of boundary layer control through tip injection on straight and swept compressor blades*. ASME-GT2005-68304,Reno-Tahoe,Nevada,USA

7.Bhaskar R., Kota V. K. and Manish C. (2007) *Experimental Study of the stability improvement by tip injection at mid chord region of axial compressor.* ISABE-2007-1267, Beijing, China

8.Gelder, T. M. (1980). *Aerodynamic Performances of Three Fan Stator Design Operating With Rotor Having Tip Speed of 337 Meters per Second*. NASA-TP-1610

9.Moore, R. D., & Reid, L. (1979). *Aerodynamic Performance of Axial Flow Stage Operated at Nine Inlet Guide Vane Angles*. NACA-TP-1510.

10. Osborn, W. M., Moore, R. D., & Steinke, R. J. (1978). *Aerodynamic Performance of a 1.35 Pressure Ratio Axial Flow Fan Stage*. NACA-TP 1299.

11. Cunnan, W. S., Stevans, W., & Urasek, D. C. (1978). *Design and Performance of a 427-Meter per Second Tip Speed Two Stage Fan Having a 2.4 Pressure Ratio*. NACA-TP-1314.

Copyright ©2009 by Cranfield University
Published by the American Institute of Aeronautics and Astronautics, Inc., with permission

12. Urasek, D. C., Gorrell, W. T., & Cunnan, W. S. (1979). *Performance of Two Stage Fan Having Low Aspect Ratio, First Stage Rotor Fan*. NACA-TP-1493.
13. Doyle, M. D., & Dixon, S. L. (1965). *The Stacking of Compressor Stage Characteristics to Reproduce an Overall Compressor Performance Map*. ARC-26867.
14.Howell, A. R., & Calvert, W. J. (1978). *A New Stage Stacking Technique for Axial Flow Compressor Performance Prediction*. Journal of Engineeering Power . Vol. 100, pp 698-703.
15. Lucas, J. G. (1958). *Use of Stage Stacking Technique for Predictive Over all Performance in Multistage Axial-Flow Compressor Utilizing Interstage-Air Bleed*. NASA MEMO 10-4-58E
16. Steinke, R. J. (1982). *A Compressor Code for Predicting Multistage Axial-Flow Compressor Performance by a Meanline Stage-Stacking Method*.NASA-TP2020

Copyright ©2009 by Cranfield University
Published by the American Institute of Aeronautics and Astronautics, Inc., with permission