Effect of Turbulence Intensity on Vortex Formation Threshold in a Jet Engine Test Cell

HO Wei Hua
University of South Africa
Department of Mechanical and
Industrial Engineering
Private Bag X6
Florida 1710
Johannesburg, South Africa
E-mail: howh@unisa.ac.za

Mark JERMY
University of Canterbury
Mechanical Engineering Department

Private Bag 4800
Christchurch 8140
New Zealand
E-mail: mark.jermy.canterbury.ac.nz

KEYWORDS

Jet Engine Test Cell, Vortex, Turbulence Intensity, JETC

ABSTRACT

Vortical structures can develop in the intakes of aircraft engines during operation in the proximity of solid surfaces. Take-off and testing in a ground facility are clear examples of such scenarios. When such a vortex is formed and ingested into the engine, potentially catastrophic damage can occur. The vortex can cause the compressor to stall, resulting in severe damage to the engine.

Procedures have been put in place to prevent such damage from occurring on the runway. However to prevent such vortices from forming, especially in the test cells, it is necessary to be able to predict the onset of the vortex or at least to understand the factors affecting the formation of such vortices.

This paper extends the scope of previous investigations by investigating the effects that increasing upstream turbulence intensity has on the vortex formation threshold.

The results show that an increase in upstream turbulence intensity increases the range of conditions over which a vortex forms. All three regimes show signs of shifting the threshold of vortex formation to lower ratio of inlet velocity over upstream average velocity (Vi/Vo) for a given ratio of inlet height over inlet diameter (H/Di).

INTRODUCTION

Vortical structures can develop in the intakes of aircraft engines during operation in the proximity of solid surfaces. Take-off and testing in a ground facility are clear examples of such scenarios. The structure of the vortex is very similar to the vortex seen in the draining of a basin or bath tub, where the streamlines spiral into the suction inlet (or outlet) with a radius of gyration that decreases as the vortex approaches the engine inlet (or bath tub outlet). One end of the vortex is anchored to a solid surface, in the case of the aero engines, or to a fluid-fluid interface in the basin or bath.

When such a vortex is formed and ingested into the engine, potentially catastrophic damage can occur. The vortex can cause the compressor to stall, resulting in severe damage to the engine.

The vortex investigated in the references in the previous sections, and the type that is investigated in this paper, deals with the kind that concentrates and thus requires the presence of vorticity in the ambient environment. In such situations, single-core vortices will form as opposed to the counter-rotating vortices described by de Siervi [1] which do not require ambient vorticity. Karlsson and Fuchs [2] modelled such vortex behaviour in a large-eddy simulation (LES) of an inlet over a ground plane. Secareanu et al. [3] validated these numerical results to particle image velocimetry (PIV) and laser doppler anemometry (LDA) measurements and obtained data on the ingestion of particles by a vortex-inlet system. Other computational fluid dynamics (CFD) studies have modelled test cell airflow, such as Gullia et al. [4] and Kodres and Murphy [5], extracting information on thrust correction factors or airflow rates, but did not modelled vortex formation.

Certain geometric and flow parameters can influence whether a vortex will form or not. The thrust of the engine, the diameter of the engine inlet, the distance from the solid surface, and the ambient vorticity, which in turn depends on the local flow field, can all encourage or discourage the formation a vortex. For example, vortices may form on takeoff if there is a sufficiently strong component of wind perpendicular to the runway, and in the test cell. Several authors have investigated the effects of geometric and flow parameters on the formation of the vortex using experimental [6,7,8] and computational methods [9,10].

This paper seeks to investigate whether increased turbulence intensity in the flow upstream of the suction inlet affects the formation of the vortex. The effect of turbulence intensity on vortex formation was not previously investigated and published.

VORTEX FORMATION IN JET ENGINE TEST CELLS

A jet engine test cell (JETC) is essentially an all-weather enclosed structure with an engine mounting mechanism intended to provide conditions for stable, repeatable and accurate post maintenance or modification engine performance testing. A pictorial

Proceedings 25th European Conference on Modelling and Simulation ©ECMS Tadeusz Burczynski, Joanna Kolodziej Aleksander Byrski, Marco Carvalho (Editors)
ISBN: 978-0-9564944-2-9 / ISBN: 978-0-9564944-3-6 (CD)

view of a typical U-shaped JETC with the main parts labelled is given in Figure 1 below.

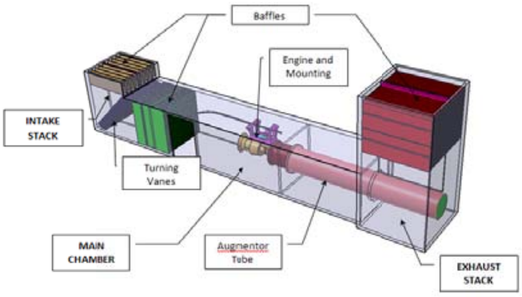

Figure 1: Main Features of a JETC

In a JETC, there is a flow of excess air beyond that required by the engine, driven by entrainment by the exhaust plume. This flow passes between the engine and the internal walls of the cell. It is quantified by a cell bypass ratio (CBR):

$$\mathrm{CBR} = 100\% \left(\frac{\dot{m}_{\mathrm{cell}} - \dot{m}_{\mathrm{engine}}}{\dot{m}_{\mathrm{cell}}}\right) \qquad (1)$$

Where $\dot{m}_{\mathrm{cell}}$ is the mass flow rate of air at the intake of the JETC and $\dot{m}_{\mathrm{engine}}$ is the mass flow rate of air jet engine including the fan and core. The CBR is distinct from the engine bypass ratio which quantifies the amount of air passing through the fan of the engine.

A commonly used rule of thumb is that a cell must have a bypass ratio of more than 80% to avoid vortex formation. Typically cells are designed with CBRs up to, and in some cases exceeding 200%. CFD simulations [11] show that a CBR below ≈70% will result in the formation and ingestion of a vortex.

Unlike the straight-forward runway case where there is a single boundary between flow regimes where a vortex forms and is ingested and not, in the JETC there exists a zone where an unsteady and deformed vortex is formed and ingested into the engine [12, 13]. These two cases are shown in Figure 2 and Figure 3 showing the boundary and the regimes. It is not clear if the unsteady vortex observed in real cells happen at conditions within this zone or is due to the unsteady nature of the surrounding flow. Glenny [14] reported that a simple opening of the laboratory door can affect the vortex in his experiments.

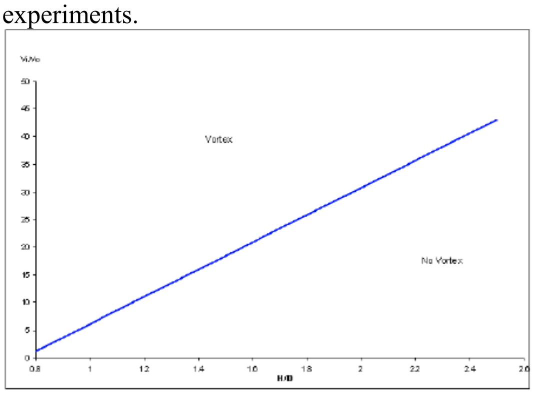

Figure 2: Flow regimes in the runway scenario

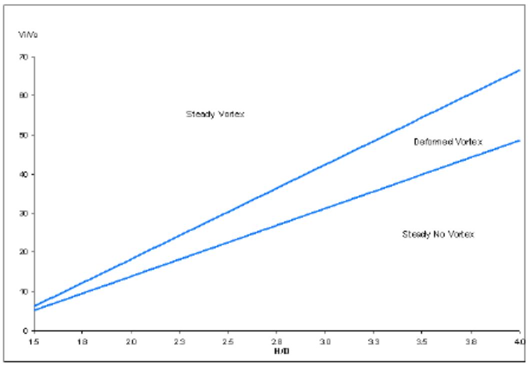

Figure 3: Flow regimes in the testcell scenario

In both the runway and testcell scenarios, the following parameters have a positive influence on the formation of such a vortex (i.e. they shift the boundary downwards and increase the conditions favouring their formation.

1. Upstream velocity gradient (amount of ambient vorticity)
2. Size of suction inlet
3. Size of boundary layer at the vortex anchoring surface

And the following parameter has a negative influence:

1. Flow Reynolds number [9]

VORTEX FORMATION IN JET ENGINE TEST CELLS

This investigation is an extension of previous investigations by Ho and Jermy [10, 11] and uses the same CFD models and solver parameters which have undergone numerous convergence tests.

The model consists of an open box with a suction inlet positioned in the box to simulate the engine. The solver used was ANSYS Fluent 12. Details of the convergence tests will not be provided here but a list of the model and solver parameters are listed below.

- Mesh density – 100 000 to 200 000 cells
- Discretisation scheme – First order discretisation scheme
- Turbulence model – SST-Kω
- Incompressible flow
- Initial conditions – Initialised at cell inlet plane

The following boundary conditions were used in the simulations.

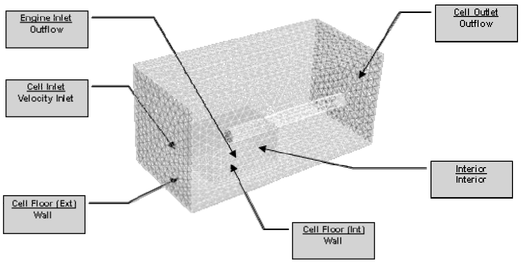

Figure 4

All the boundary conditions are self-explanatory with the exception of outflow. Outflow is a boundary condition available for use by ANSYS Fluent and is a percentage. It allows a quick and easy way assign amount of flow through each of the Outflow boundaries. A user-defined function (UDF) was used, at the upstream and cell inlet of the take-off and test cell scenarios respectively, to simulate ambient vorticity. The ambient vorticity was imposed by applying a constant gradient to the component of velocity parallel to the axis of the intake. The gradient is perpendicular to the flow and parallel to the ground in the horizontal plane.

The details of the engine was not explicitly modelled, instead the engine inlet plane was modelled as an outflow. Together with boundary "cell_outlet" (also an outflow boundary condition), it allows a specific CBR to be assigned to each solution.

At boundaries where walls were used, standard wall functions were used.

Turbulent Intensity

Turbulent intensity or turbulent level is the ratio of the root-mean-square of the turbulent velocity fluctuations and the Reynolds averaged mean velocity.

$$I = \frac{\sqrt{\frac{1}{3}(u_x^2+u_y^2+u_z^2)}}{\sqrt{U_x^2+U_y^2+U_z^2}} \qquad (2)$$

Where I = turbulence intensity
u = turbulent velocity fluctuations
U = mean velocity

ANSYS Fluent 12 allows direct input of turbulence intensity and is applied to the "cell_inlet" boundary using the "turbulence intensity / hydraulic diameter" input with the hydraulic diameter being the cell_inlet dimensions.

The range of turbulence intensity used in the calculations is from 0.5% to 50% and the range of H/Di used is from 2 to 4. The range of turbulence intensity used in the simulations is larger than that which is usually encountered in a JETC (up to 10%). Turbulence intensity above 10% is unlikely to be encountered but was investigated to establish trends over a larger range of values.

Searching for the threshold

The search for the threshold or boundary for the different flow regimes follows following steps:

1. A low value of CBR is chosen by a combination of the outflow values at the "engine_inlet" and "cell_outlet" boundaries. An average cell inlet velocity is imposed together with a velocity gradient using a UDF at the "cell_inlet" boundary.
2. Outflow value at the "cell_outlet" boundary is altered to change the CBR value until the threshold is found.
3. The solution was considered to have converged when the residuals have fallen to an acceptable range and/or have stabilised.

The outflow value at the "cell_outlet" boundary was changed in increments of 0.01 resulting in a change in Vi/Vo of less than 1.2%.

Every set of simulation was initialised at the "cell_inlet" boundary with values calculated at that plane to prevent the memory effect observed by Ridder and Samuelsson [15] from previous calculations to affect the subsequent ones.

RESULTS

The results of the vortex formation threshold is presented in a table (Table 1) as well as H/Di vs Vi/Vo graphs (Figure 5 – Figure 10) similar to previous publications [6,10] on this subject.

The points on the graphs show the threshold location with regions above encouraging vortex formation and vice versa.

Table 1: Vi/Vo threshold values for different H/Di and Turbulence Intensity

T.I. = 0.5%		
H/Di	Vortex	No Vortex
2	17.752	14.593
3	38.605	28.923
4	69.211	51.744
T.I. = 10%		
H/Di	Vortex	No Vortex
2	17.450	14.388
3	38.605	28.565
4	68.062	50.783
T.I. = 20%		
H/Di	Vortex	No Vortex
2	17.303	14.388
3	38.605	28.478
4	67.502	50.783
T.I. = 50%		
H/Di	Vortex	No Vortex
2	17.016	14.189
3	38.605	28.044
4	66.951	50.470

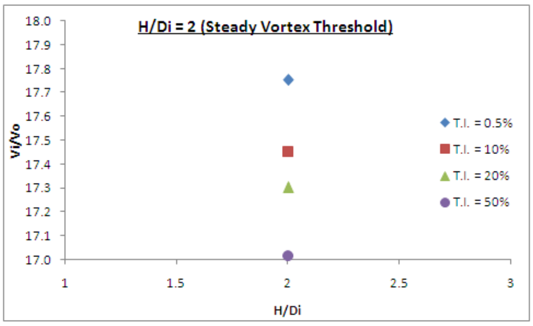

Figure 5

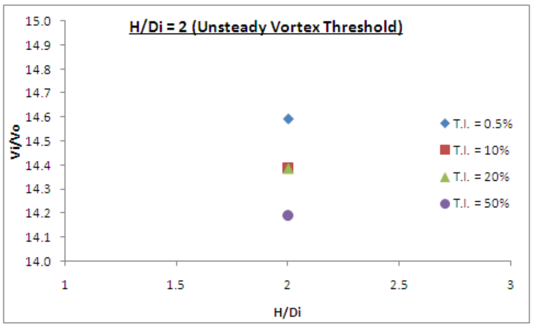

Figure 6

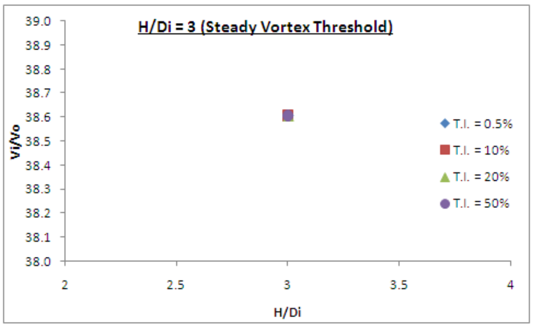

Figure 7

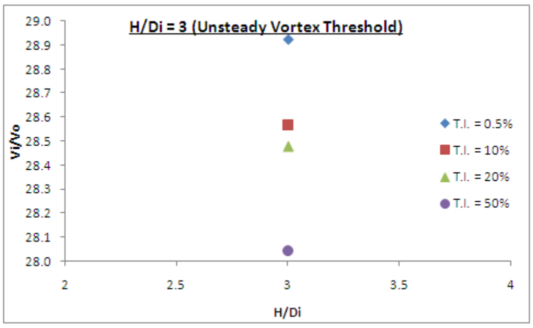

Figure 8

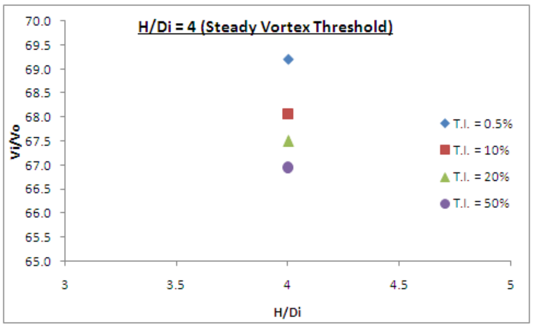

Figure 9

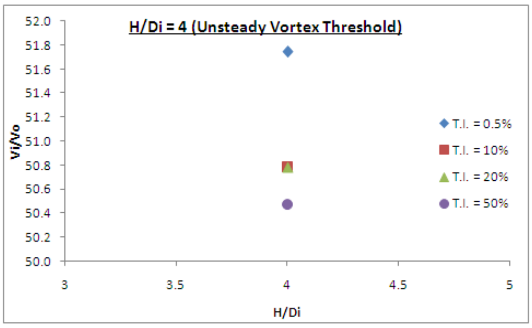

Figure 10

DISCUSSIONS

Figure 5 to Figure 10 clearly shows that increasing turbulence intensity lowers the threshold point on both the steady and unsteady vortex regimes. This indicates an increase in the conditions favouring the formation of vortices thus making it more probable for a vortex to form. Although some scenarios shows overlapping threshold points (Figure 6, Figure 7 and Figure 10), the overall picture is that of decreasing threshold values. Figure 7 especially shows all points lying on the same point. This is unlikely as it is the only such case and should be an abnormal set of results. However it has been included for completeness of presentation.

Increasing turbulence intensity can increase or decrease the instantaneous velocity gradient and/or mean velocity as “sign” of the velocity fluctuations are negated by the squaring of them in the calculations of the turbulence intensity and both signs exist in a turbulent flow.

Ridder and Samuelsson [15] observed a memory effect for the vortices i.e. the threshold value of Vi/Vo is lower when moving from a regime where there is a vortex to one where there isn’t and vice-versa. This is potentially an explanation for the observations in the simulations. Temporary increment of velocity gradients (or mean velocity), due to velocity fluctuations, induces a vortex to form and this vortex requires a lower Vi/Vo value to disappear.

The threshold when moving from a regime of no vortex to vortex is termed “increasing threshold” in this document because the region of no vortex lies below the region of vortex in the graphs. Conversely, “decreasing threshold” is used to indicate the threshold when moving from a regime of vortex to no vortex. “Mean threshold” indicates the threshold when no change (or tuning) of upstream flow conditions are applied. This is unlikely to be carried out in a physical experiment but is the case for simulations detailed in this paper as well as previous work by Ho and Jermy [9 -13].

No studies have been made so far measuring the relative distance between the “increasing” and “decreasing” threshold lines and the “mean” threshold line. The observed results could indicate that they are not at equidistance apart.

It is also unclear how long favourable conditions have to hold for the vortex to remain established once “unfavourable” conditions have been re-established and vice-versa.

CONCLUSIONS

Increasing turbulence intensity increases the probability of a vortex forming by shifting the threshold to a lower Vi/Vo value at a certain H/Di value.

This may be due to the memory effect of this flow phenomenon observed by Ridder and Samuelsson [15]. Once a vortex is formed due to instantaneous higher velocity gradient or low mean velocity, it requires a lower Vi/Vo value to remove this vortex. Since the fluctuations can happen in both directions, the lowering of the threshold indicates that the distance between the "increasing", "decreasing" and "mean" thresholds are not equidistant apart.

It is also unclear how favourable conditions have to hold for the vortex to remain established once unfavourable conditions have been re-established.

---

[1] De Siervi F., Viguier H. C., Greitzer E. M., and Tan C. S., "Mechanisms of inlet vortex formation", J. Fluid Mech., 124, 173–207, 1982.

[2] Karlsson A. and Fuchs L., "Time evolution of the vortex between an air inlet and the ground", AIAA paper 2000-0990, 2000.

[3] Secareanu A., Morioanu D., Karlsson A. and Fuchs, L., "Experimental and numerical study of ground vortex interaction in an air-intake", AIAA paper 2005-1206, 2005.

[4] Gullia, A., Laskaridis, P., Ramsden, K.W., and Pilidis, P. "A preliminary investigation of thrust measurement correction in an enclosed engine test facility", AIAA paper 2005-1128, 2005.

[5] Kodres, C. A. and Murphy, G. L. "Jet-engine test cell augmenter performance", J. Propuls. Power, 14(2),129–134, 1998.

[6] Nakayama A. and Jones J. R. "Vortex formation in inlet flow near a wall", In the 34th Aerospace Sciences Meeting and Exhibit, AIAA 96-0803, 1996.

[7] Liu W, Greitzer E. M., and Tan C. S. "Surface static pressure in an inlet vortex flowfield", ASME J. Engineering Gas Turbines Power, 107, 387–393, 1985.

[8] Shin H. W., Cheng W. K., Greitzer E. M., Tan C. S. and Shippee C. L. "Circulation measurements and vertical structure in an inlet-vortex flow field", J. FluidMech, 162, 463–487, 1986.

[9] Jermy M. and Ho W. H., "Location of the vortex formation threshold at suction inlets near ground planes by computational fluid dynamics simulation", Proceedings of the I Mech E Part G Journal of Aerospace Engineering Volume 222 Number 3 pp 393 – 402, 2008.

[10] Ho W. H. and Jermy M. "Formation And Ingestion Of Vortices Into Jet Engines During Operation", IAENG TRANSACTIONS ON ENGINEERING TECHNOLOGIES VOLUME 1 - Special Editions of the International MultiConference of Engineers and Computer Scientists 2008 pp 132 – 143, 2008.

[11] Ho W. H., Dumbleton H. and Jermy M. C., "Effect of Upstream Velocity Gradient on the Formation of Sink Vortices in a Jet Engine Test Cell", Proceedings of the International MultiConference of Engineers and Computer Scientists (IMECS), pp 1767 – 1772, 2008

[12] Ho W. H. and Jermy M., "Validated CFD simulations of vortex formation in jet engine test cells", Proceedings of the 16th Australasian Fluid Mechanics Conference (AFMC), pp 1102 – 1107, 2007

[13] Ho W. H., Jermy M. and Dumbleton H., "Formation of Sink Vortices in a Jet Engine Test Cell", IAENG Engineering Letters Volume 16 Issue 3 pp 406 – 411, 2008.

[14] D. E. Glenny, "Ingestion of debris into intakes by vortex action", Aeronautical Research Council CP no. 1114, 1970.

[15] S. O. Ridder and I. Samuelsson, "An experimental study of strength and existence domain of ground-to-air inlet vortices by ground board static pressure measurements", Stockholm Royal Institute of Technology, KTH AERO TN 62, 1982.

AUTHOR BIOGRAPHIES

Wei Hua HO took a BEng (Hons) in Mechanical and Production Engineering at Nanyang Technological University, Singapore in 2004 and a Ph.D. at the University of Canterbury, NZ in 2009 for work on vortex and infrasonic noise problems in a jet engine test cell. In between the two degrees, he worked for a couple of years at Singapore Technologies Aersopace Ltd as a mechanical systems engineer where he worked on various manned and unmanned aircraft platforms. In 2010, he was appointed as a Senior Lecturer at the University of South Africa. His research interests include vortex formation, bio-fluids flow and industrial flow. His email address is howh@unisa.ac.za

Mark Jermy took a B.Sc. Hons. in Physics at the University of Birmingham, UK in 1993 and a Ph.D. at the University of Kent in 1997 for work on the structure-property relationship of glasses. He worked for a couple of years for the UK Ministry of Defence and then took up a postdoc position at Cranfield University, where he worked on light scattering measurements of fuel injection sprays. He was appointed Lecturer at Cranfield. In 2005 he moved to the University of Canterbury in Christchurch, New Zealand, where he is a Senior Lecturer. His research interests include vortex formation, cycling aerodynamics, biofluid mechanics, kinetic theory CFD methods and blood spatter pattern formation in forensic investigations. His email address is mark.jermy@canterbury.ac.nz