Location of Vortex Formation Threshold at Suction Inlets near Ground Planes – Ascending and Descending Conditions

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Abstract—Vortices can develop in intakes of turbojet and turbo fan aero engines during high power operation in the vicinity of solid surfaces. These vortices can cause catastrophic damage to the engine. The factors determining the formation of the vortex include both geometric dimensions as well as flow parameters. It was shown that the threshold at which the vortex forms or disappears is also dependent on the initial flow condition (i.e. whether a vortex forms after stabilised non vortex flow or vice-versa). A computational fluid dynamics study was conducted to determine the difference in thresholds between the two conditions. This is the first reported numerical investigation of the "memory effect". The numerical results reproduce the phenomenon reported in previous experimental studies and additional factors, which had not been previously studied, were investigated. They are the rate at which ambient velocity changes and the initial value of ambient velocity. The former was found to cause a shift in the threshold but not the later. It was also found that the varying condition thresholds are not symmetrical about the neutral threshold. The vortex to no vortex threshold lie slightly further away from the neutral threshold compared to the no vortex to vortex threshold. The results suggests that experimental investigation of vortex formation threshold performed either in vortex to no vortex conditions, or vice versa, solely may introduce mis-predictions greater than 10%.

Keywords—Jet Engine Test Cell, Unsteady flow, Inlet Vortex

I. INTRODUCTION

VORTICES can develop in the intakes of aero engines during high power operation near solid surfaces such as the runway or the walls of Jet Engine Test Cells (JETC). This phenomenon can occur during take-off, ground run of engines or during engine tests in a JETC. The structure of the vortex is very similar to vortices seen in draining basins or bath tubs. The fluid streamlines spiral towards and into the suction inlet with decreasing radius of gyration. The other end of the vortex is anchored to a nearby solid surface or an interface, such as the case of draining basins where the anchor is at the liquid-air interface.

Various factors determine whether a vortex will form. These include the following:

- Thrust of the engine or suction power in the case of a generic suction inlet
- Amount of ambient vorticity
- Diameter of the engine inlet or suction inlet
- Distance of the engine or suction inlet from the solid surface or interface

The first two factors are non-geometric factors and depend strongly on the engine operating parameters and local flow field respectively. For example, vortices may form at configurations where previously no vortices were detected because of a new engine setting or an unusually strong component of crosswind on the runway or distortion in the JETC inlet velocity profile. This distortion in the JETC inlet velocity profile may be a result of cell geometry, or crosswind at the top of the inlet stack [1].

These vortices concentrate ambient vorticity leading to single core vortices forming at the engine or suction inlet. The formation and ingestion of such vortices can potentially lead to catastrophic damage to the engine. In addition to physical damage caused by ingestion of foreign objects, commonly termed foreign object damage (F.O.D.), the strong pressure variations within the vortex core can also cause the compressor to stall.

In the formation of such vortices, there exists a blow-away velocity upstream of the inlet. Above this threshold, the vortex core is convected downstream and disconnected from the inlet (blown-away). Conversely if the upstream air velocity is below the blow-away velocity, a vortex may be formed, subjected to other conditions being favourable.

Equally important is the distance between the engine (or suction inlet) and the solid surface. If this distance is too large, no stagnation point (a point with a diverging radial velocity profile) will form on the surface and the vortex cannot form. In other words, the capture stream-tube does not intersect with any solid surface.

The velocity condition is expressed as the ratio between the suction inlet velocity (Vi) and the ambient velocity (Vo), Vi/Vo. The distance condition is expressed as the ratio between the distance between the engine centreline and the solid plane (H) to engine diameter (Di), H/Di. Sometimes D is used instead of Di in studies. Fig shows the principal parameters as described above.

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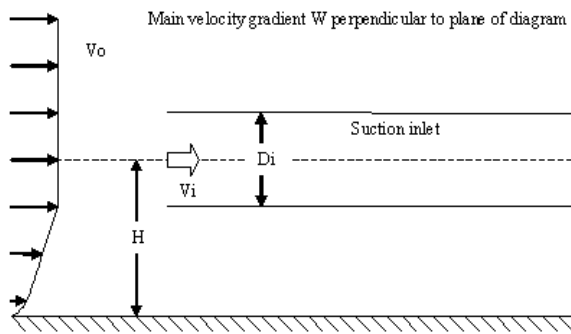
Fig. 1 Sketch showing the principal parameters

At intermediate values, both conditions are dependent on each other, i.e. a H/D_i value that is too high at low V_i/V_0 may not be, at higher V_i/V_0 values.

A number of studies [2,3,4,5] have been reported the use of computational fluid dynamics to investigate various aspects of the phenomenon such as the unsteady vortex behaviour and the ingestion of particles.

Besides understanding the physical characteristics of the vortex, understanding the conditions which encourages the formation of the vortex is also very important. Both computational methods [6,7,8,9] and experimental methods [10,11,12] have been utilised to investigate the conditions permitting the formation of vortices Fig and Fig shows the computational and experimental results.
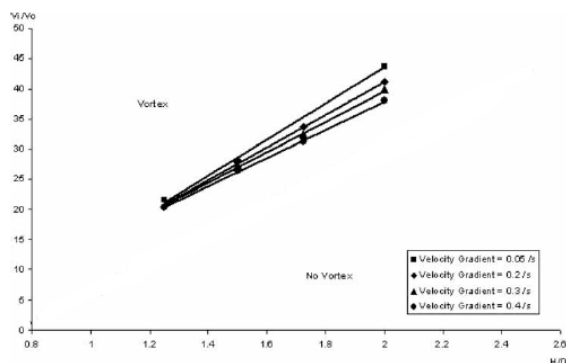

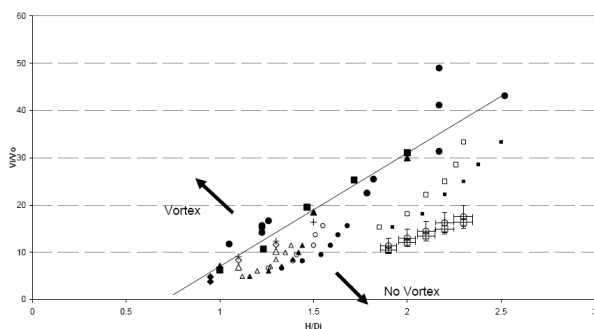Fig. 2 Vortex formation threshold from computational studies [6]

Fig. 3 Vortex formation threshold from experimental studies [6]

The computational results agree very well with previous experimental results qualitatively. The quantitative difference in the threshold could be due to various geometric and flow conditions as reported by Ho and Jermy [6,7] or to the memory effect that Ridder and Samuelsson [13] reported. It is also unclear whether the experimental results had the same level of sensitivity as the simulations. Some of the experiments did not use actual visualisation of a vortex as a means of detecting a vortex but used other manifestations such as the lifting of beads instead.

To date, there have been no reports of any computational study on the memory effect.

Note that the computational studies of Ho and Jermy always initialised the flow field before solving for a suction inlet – ambient velocity ratio, in an intentional manner to eliminate the memory effect [6]. This is not the same as moving from conditions without a vortex to one with a vortex. In the initialised CFD simulations, a stable no vortex flow did not exist before the formation of the vortex.

II. MEMORY EFFECT OF VORTEX FORMATION PHENOMENON

Ridder and Samuelsson [13] reported that "while determining the blow-away height of an inlet vortex a pronounced lag in the vertical distance was found between an ascending inlet with the vortex just having collapsed and a descending inlet with the vortex just being established". Note that Ridder and Samuelsson's "ascending" and "descending" describes physical movement of the inlet. This is opposite to the operating condition on the Vi/Vo vs H/D graph. The ascending inlet corresponds to moving downwards on the graph where a prevailing vortex collapses and vice versa. The second definition will be used from this point forward, and the term ascending threshold would indicate moving upwards on the Vi/Vo vs H/D graph and vice versa.

This indicates that there are potentially other "sub-thresholds" lying on either side of the computational thresholds. These sub-thresholds are a direct consequence of the inertial and viscous forces present. The distance between the "neutral threshold" in previous computational studies and these sub-thresholds is hypothesized to be affected by the following factors:

1. Ascending or descending scenarios
2. Rate at which V_i (or V_0) changes
3. The magnitude difference between the "starting" and threshold conditions, i.e. whether the starting conditions lie closer or further from the neutral threshold.
4. Flow and geometry conditions such as velocity gradient and engine diameter.

Understanding of the memory effect together with qualitative investigations and quantitative measurement of the two sub-thresholds is critical to the accurate prediction of the conditions that results in a vortex forming. It is also a critical step to bridge the gap between future computational and experimental studies in this area. Unlike computational studies where each set of calculation can be initialised from a particular value easily, experimental studies will almost always involve some adjustments to the experimental

parameters (either intentional or unintentional). These adjustments will inevitably lead to some shift in the "observed threshold" due to the memory effect.

Another important reason for the understanding of the memory effect lies in conditions where the ambient (take-off) or JETC inlet flow have high turbulent intensity. Ho and Jermy [14] reported that an increase in turbulent intensity lowers the threshold thus increasing the probability of a vortex forming. It was hypothesized that this may be due to non-symmetry of the location of the two sub-thresholds from the neutral threshold. If either the ascending or descending threshold is significantly further from the neutral threshold compared to the other then a change in turbulent intensity may shift the "threshold" in either direction. It is not clear how long the "instantaneous" conditions need to persist for a vortex to form or dissipate.

III. SCOPE OF INVESTIGATION

The vortex investigated in previous computational and experimental investigations referenced in this document as well as the type that is investigated in this paper deals with single core vortices that result from a concentration of ambient vorticity. This is opposed to the type which does not require ambient vorticity and results in two counter-rotating vortices described by de Siervi et al. [15] and Murphy and MacManus [16]. The same counter-rotating vortices were also observed when the upstream velocity gradient is less than 0.001/s [6].

At the time of writing, only the first three factors that were hypothesized to have an effect on the memory effect are investigated and they are:

1. Ascending or descending scenarios
2. Rate at which Vo (or Vi) changes
3. Different starting conditions

Only the take-off or engine ground run scenarios are being investigated and no JETC scenarios were completed.

IV. METHODOLOGY

3D CFD simulations of a cylindrical inlet of negligible thickness over a ground place were used in this study. The model is the same model used in previous simulations by Jermy and Ho [6]. The flow region was split into two regions of differing mesh densities to reduce mesh size and hence computation resources in regions far away from the suction inlet. Higher mesh density was used in the region near the suction inlet and where the vortex forms, under the appropriate conditions. A boundary layer was modelled with 4 layers (thickness of 0.1m for the first layer), each layer increases by a factor of 1.2 from the previous. Standard wall functions were used. The model underwent a number of convergence tests as detailed in [6].

The size of ambient space around the suction inlet is as follows:

- upstream – 5 x suction inlet diameter
- upstream – 5 x suction inlet diameter
- downstream – 10 x suction diameter
- sides – ≈8 x suction inlet diameter

- ceiling – ≈7 x suction inlet diameter

This was found after a series of tests were conducted to determine the optimum size. Fig below shows a pictorial view of the model. The calculations were run on only one geometric model with a suction inlet diameter (D) of 1m and an H/D value of 2.0.
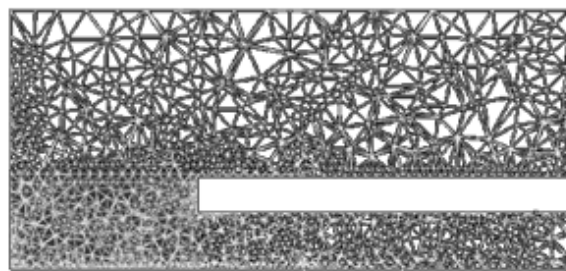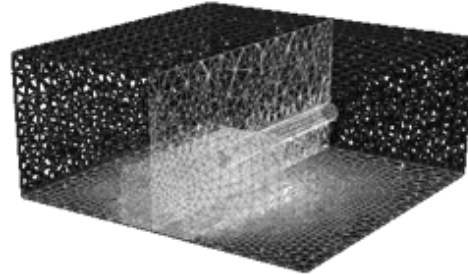

Fig. 4 Flow Model

The solver used was ANSYS Fluent 13.0 with the following parameters:

- Mesh density – 104087 cells
- Discretisation scheme – first order discretisation scheme
- Turbulence model – SST-Kω
- Incompressible flow
- Initial conditions – Solution was initialised at cell inlet plane

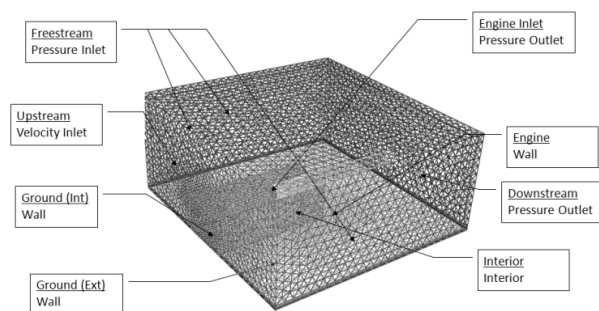The following boundary conditions (as they are named in ANSYS Fluent) were used during the simulations.

Fig. 5 Boundary Conditions

The change in conditions was simulated through the increase and decrease of Vo. The model was initialised with a Vo value below or above the neutral threshold value and gradually increased or decreased at a fixed rate through the

use of a UDF function. The neutral threshold value was taken from [6]. Three rates of change (0.1/s, 0.05/s and 0.01/s) of V_0 were solved. The upstream velocity gradient was 0.2/s and two initial average V_0 values corresponding to +/- 1m/s and +/- 0.5m/s were solved (depending on whether it was from a scenario with no vortex to one with a vortex and vice versa.

It was anticipated that it would take a period of time for a vortex to form in conditions favouring its formation. This would be dependent on the geometry of the suction inlet. Thus it was necessary to conduct an initial experiment to find out the time needed for a vortex to form in constant favourable conditions. For descending conditions, it will be necessary to have an initial time (say X secs) at constant Vo in the beginning of the simulation to allow the vortex to form before increasing Vo. This initial condition may or may not be necessary for ascending conditions depending on the total time before a vortex forms in each case. If the total time it takes for a vortex to form in each simulation (without the initial time) is much longer than the time it takes a vortex to form in constant favourable conditions, then it is not necessary to implement the constant Vo condition.

A vortex was deemed to have been formed when vector plots on the ground show clear circulatory flow. Fig illustrates this.
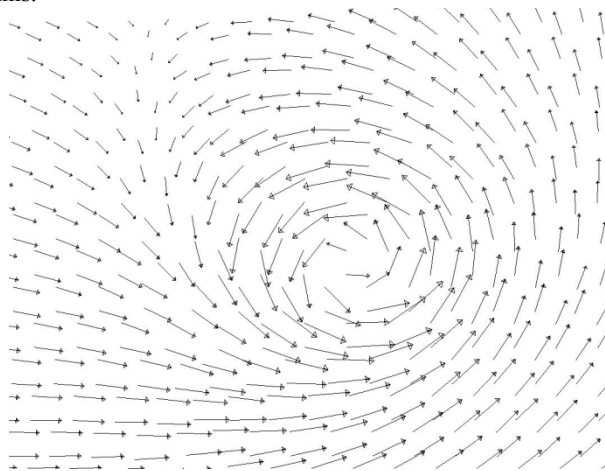

Fig. 6 Velocity plots of a vortex

V. RESULTS AND DISCUSSION

All time steps were solved to 3000 iterations and the eventual residuals were less than 5×10^{-3} with a large majority less than 5×10^{-4}.

A. Duration for a vortex to form under favourable conditions

In order to accurately simulate a descending vortex (where a vortex dissipates after being formed), it is necessary to know the amount of time needed for a vortex to form under favourable conditions.

This will be dependent on the size of the suction inlet and the distance from the solid surface. Thus the current set of results is only applicable to an engine size of around 1m with a H/D ratio of 2.0.

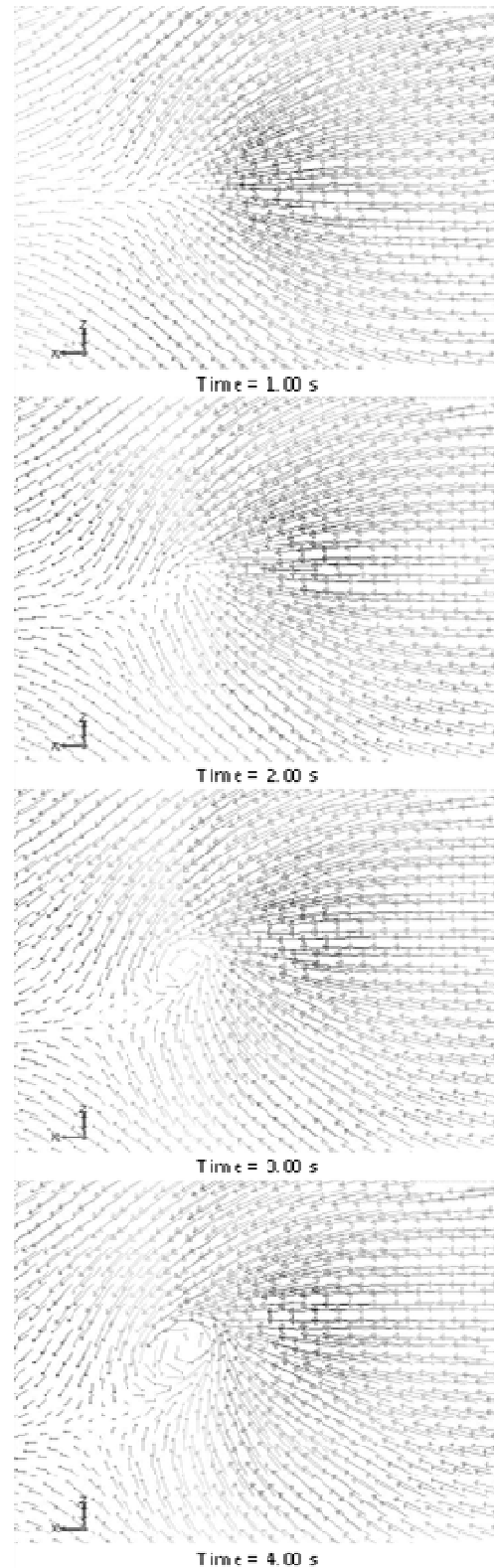Time = 1.00 s

Time = 2.00 s

Time = 3.00 s

Time = 4.00 s

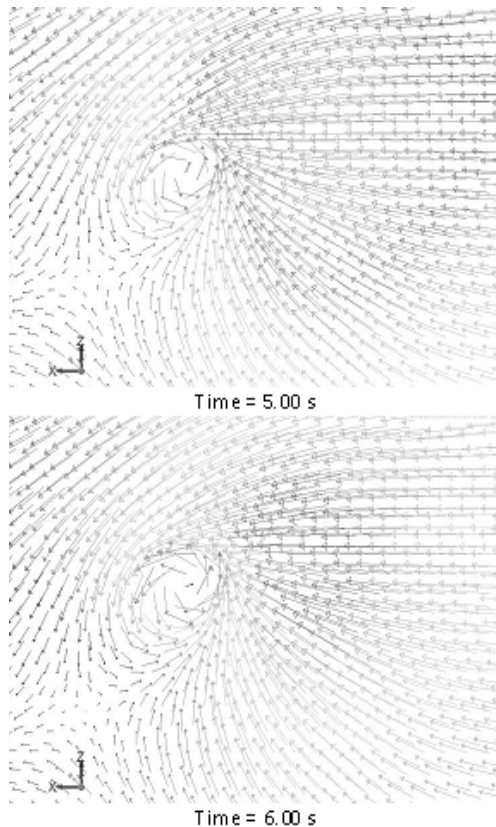Fig. 7 Velocity vector plots showing the formation of a vortex (1-4 secs)

Fig. 8 Velocity vector plots showing the formation of a vortex (5-6 secs)

Fig shows the formation of a vortex under favourable conditions at time-steps of 1 sec interval. The upstream velocity was kept constant at velocity gradient of 0.2/s with an average velocity difference of -1m/s from the neutral threshold value.

Thus for simulations of descending conditions, it is necessary to include a buffer time of 5 secs for the vortex to form before commencing the increase in Vo. For ascending conditions, it was found that a vortex took much longer than 5 secs to form in all simulations. Thus it is not necessary to include this buffer time.

B. Dissipating of a vortex

As mentioned earlier in this paper, as the blow-away velocity increases in the presence of a vortex, the vortex core gets convected downstream and eventually gets blown away. Fig illustrates this process.
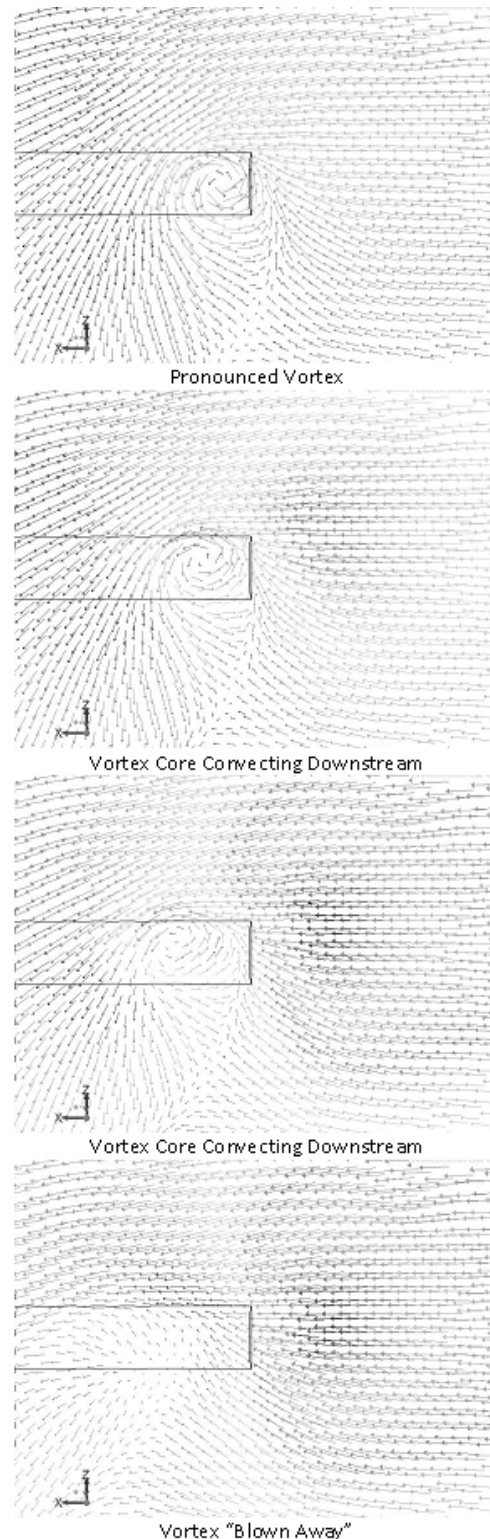

Fig. 9 Vortex being blown away

In Fig, the flow direction is from right to left in the positive X-direction. The white rectangle is the suction tube with the right-most edge being the inlet. The pictures from top to bottom show the effect of increasing upstream velocity Vo.

The dissipation of the vortex is shown clearly where from an almost perfect circular vortex core (top picture) shifts downstream showing signs of elongation when Vo is increased (2nd and 3rd picture). Eventually the core is not longer able to be sustained (4th picture).

C. Ascending and. Descending Threshold

CFD results agree with previous findings by Ridder and Samuelsson [13]. If a vortex has formed, it requires a higher blow-away velocity (compared to the neutral case) to dissipate the vortex and vice versa. The results are presented in TABLE .

TABLE I
ASCENDING AND DESCENDING THRESHOLD

	Neutral	Ascending	Descending
Vi (m/s)	151.18	151.48	151.97
Vo (m/s)	3.75	3.60	4.40
Vi/Vo	40.32	42.08	34.54

The calculated values of Vi/Vo have uncertainty of +/-1.4% and +/- 1.2% for ascending and descending respectively.

D. Different rate of change of Vo

Different rate of change of Vo affects the position of both the ascending as well as descending threshold.

TABLE II
ASCENDING THRESHOLD FOR DIFFERENT VO CHANGE RATES

Rate	Neutral	Ascending		
		0.01/s	0.05/s	0.1/s
Vi (m/s)	151.18	151.48	151.35	151.19
Vo (m/s)	3.75	3.60	3.35	3.08
Vi/Vo	40.32	42.08	45.18	49.17
Uncertainty (+/- %)		1.38	4.43	5.63

TABLE III
DESCENDING THRESHOLD FOR DIFFERENT VO CHANGE RATES

Rate	Neutral	Descending		
		0.01/s	0.05/s	0.1/s
Vi (m/s)	151.18	151.97	152.21	152.29
Vo (m/s)	3.75	4.40	4.78	4.98
Vi/Vo	40.32	35.54	31.88	30.61
Uncertainty (+/- %)		1.14	1.55	2.48

The results show that a quicker ascend or descend rate "shifts" the threshold further away from the neutral threshold.

The results also suggest that descending shifts the threshold further from the neutral than the ascending. However, more calculations need to be performed before a more definite conclusion can be drawn on this.

Increasing Vo at a rate of 0.01s, from a regime with a vortex, may result in a mis-prediction of threshold conditions of up to 4.4%. Other conditions may lead to larger mis-predictions. Table gives the other values for the other calculation scenarios.

TABLE IV
VI/VO PREDICTION SHIFT PERCENTAGE (FROM NEUTRAL)

Rate	Neutral	Ascending		
		0.01/s	0.05/s	0.1/s
Vi/Vo shift (%)	0	4.4	12.1	21.95

Rate	Neutral	Descending		
		0.01/s	0.05/s	0.1/s
Vi/Vo shift (%)	0	11.9	20.9	24.1

The results indicate that any experiments conducted with the aim of getting the vortex formation threshold should be conducted in both an ascending as well as descending manner. So far only Ridder and Samuelsson have indicated clearly that it was performed [13].

The difference between the ascending and descending thresholds (at the same change rates) indicates that increased turbulent intensity in flows maybe lower the threshold [14]. A highly turbulent flow, with mean conditions at the no vortex regime, may cross the ascending threshold, thus going into the vortex regime, but not the descending threshold. This may have the effect of lowering the formation threshold. Although it takes between 4 – 5 secs for a vortex to form in constant favourable conditions, it is not clear what happens in fluctuating flows which encompasses the ascending threshold and with instantaneous conditions constantly crossing one of the sub-thresholds.

Fig. 10 below illustrates a scenario where the fluctuating conditions encompass the ascending threshold. The relative locations of the three thresholds are not drawn according to scale with the double-headed arrow indicates the maximum range of fluctuation in conditions.
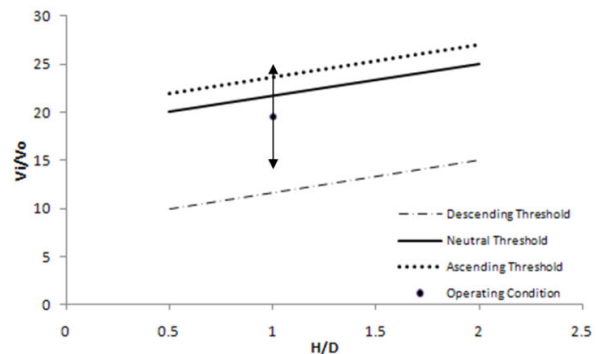

Fig. 10 Highly turbulent intensity flow

E. Starting at different values of Vo

TABLE V
DIFFERENT STARTING VALUES OF VO (ASCENDING)

	Neutral	Ascending			
		0.01/s	0.05/s	0.01/s	0.05/s
Starting aver. Vo		4.75		4.25	
Vi (m/s)	151.18	151.47	151.31	151.47	151.33
Vo (m/s)	3.75	3.60	3.30	3.60	3.35
Vi/Vo	40.31	42.07	45.85	42.08	45.17
Uncertainty (+/- %)		1.38	4.43	1.38	4.43

TABLE VI
DIFFERENT STARTING VALUES OF VO (DESCENDING)

	Neutral	Descending			
		0.01/s	0.05/s	0.01/s	0.05/s
Starting aver. Vo		2.75		3.25	
Vi (m/s)	151.18	151.97	152.22	151.98	152.12
Vo (m/s)	3.75	4.40	4.80	4.40	4.65
Vi/Vo	40.31	34.54	31.71	34.54	32.71
Uncertainty (+/- %)		1.14	1.55	1.14	1.59

The results do not show any indication that commencing with different average values of Vo have any significant effect on the thresholds. Both starting values are still a good difference from the neutral value, it is not clear if there will be any effect if the starting value is very close to the neutral threshold value. However it is unlikely that the starting Vo will be close to the neutral value very often in experiments.

VI. CONCLUSIONS

The CFD-based methods used in this study successfully reproduced the ascending and descending thresholds reported in previous experimental studies. The trends observed in the numerical results are in qualitative agreement with the experimental data. When a vortex has formed (descending), it requires a higher blow-away velocity compared to the neutral value to dissipate the vortex. Conversely when a stable no vortex flow has been achieved (ascending), it required to lower the blow-away velocity below the neutral threshold values for a vortex to form. This of course indicates that the ascending threshold has higher Vi/Vo values compared to the descending threshold.

Further, it was observed that different rates of change of Vo can affect the threshold value both in ascending and descending conditions. A quicker ascend (or descend) shifts the threshold by a larger amount. At the same rate of change, the descending threshold is further from the neutral threshold compared to the ascending threshold. However more calculations at different geometries are necessary before this can be conclusively ascertain.

Lastly, different starting velocities (as long as they are in the same regime i.e. vortex or no vortex) do not seem to have an effect on the threshold. However it is not certain if there will be any effects when the starting velocities are very close to the neutral threshold values.

At the current geometry, it was found that it took around 4-5 secs for a vortex to form.

The difference between the ascending and descending thresholds (at the same change rates) indicates that increased turbulent intensity in flows maybe lower the threshold [14]. A highly turbulent flow, with mean conditions at the no vortex region, may cross the ascending threshold, thus going into the vortex region, but not the descending threshold. Although it takes between 4 – 5 secs for a vortex to form in constant favourable conditions, it is not clear what happens in fluctuating flows which encompasses the ascending threshold and with instantaneous conditions repeatedly crossing only one of the sub-thresholds.

These results confirm that a "memory effect" exists for such flow situations. Thus, when conducting experiments, it is critical to perform them in both ascending and descending conditions. Depending on the relative geometries of experimental set-ups as well as other flow parameters, it is possible that mis-predictions of more than 10% may be present if this is not performed. It is also recommended to change the conditions as gradual as possible to reduce the mis-predictions.

RECOMMENDATIONS FOR FUTURE WORK

As a continuation of the current studies, it is recommended to conduct CFD simulations and experimental investigations on geometries relating to an enclosed test cell using similar methodologies. It will also be interesting to conduct investigations on runway and test cell models using other methods of changing flow conditions such as changing Vi or H with Vi having more foreseeable practical implications.

Of particular interest will be the effect of fluctuating or high turbulent intensity upstream flows with conditions encompassing one of the sub-thresholds, as discussed in section V.D on page 6.

ACKNOWLEDGEMENT

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