PHD THESIS

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STUDY OF LARGE–SCALE COHERENT STRUCTURES IN THE NEAR FIELD AND TRANSITION REGIONS OF A MECHANICALLY OSCILLATED PLANAR JET

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November 2008
Chapter 3

Experimental Results & Discussion

“The truth is rarely pure and never simple.”

Oscar Wilde

The Importance of Being Earnest (1895)

3.1 Flow Visualisation Results & Regime Classification

A methodical approach was chosen for initial flow visualisation experiments. The stroke over height ratios \( S/h \) varied from 0.5 to 10.0, the oscillation frequencies \( f_o \) from 0.25 to 6.0 Hertz and nozzle exit velocity in the form of the Reynolds number \( Re_h \) ranged from 1000 to 9810. Over 240 individual flow cases were recorded as shown in Table H.1 in Appendix H.

Flow visualisation experiments above an oscillation frequency of 6 Hertz were not performed as structures were generally unrecognisable above this frequency. At high \( S/h \) ratios additional intermediate frequency steps were also recorded to capture the rapid changes in flow features that were observed during experimentation.

Analysis of the flow visualisation led to the identification of three different classes of flow, each with very distinct flow characteristics. These flow classes or regimes have been termed:

- Base Flow Regime
CHAPTER 3. EXPERIMENTAL RESULTS & DISCUSSION

- Resonance Flow Regime
- Bifurcation Flow Regime

and their characteristics and development are discussed in the following sections.

In general, it is worth noting that all three regimes are symmetrical across the oscillation centreline, with most flow structure development occurring at and around Top Dead Centre (TDC) and Bottom Dead Centre (BDC) as is shown in more detail below.

3.1.1 Base Flow Regime

The flow regime most commonly encountered and over a wide range of different flow conditions has been termed the Base Flow Regime or Base Regime, as all other regimes can be traced back to this original flow regime in their flow features and large-scale coherent structures. Figure 3.1.a shows a schematic representation of the coherent structures as they appear when the jet nozzle is at BDC. All large-scale structures form at either TDC or BDC and are fully formed by the time the oscillation reaches the opposing side of the stroke. The flow regime itself is characterised by the generation of two counter-rotating vortices within each half-cycle of oscillation. One vortex is generally larger than the other and forms along the trailing edge of the jet as it starts moving from rest at TDC or BDC. The smaller vortex forms on the leading edge of the jet as the nozzle slows down to come to a full stop at TDC and BDC. This leading edge vortex is generally engulfed by the larger vortex from the opposing half of the stroke after moving downstream with the flow for around one to two full oscillation cycles.

The larger vortex travels for a large distance in a near-parallel fashion to the oscillation centreline and undergoes very little spreading in the lateral direction. No vortex pairing of the larger vortices occurs as they move downstream up until to a point where all large-scale structures dissipate very abruptly and completely instead of pairing.

Figure 3.1.b & 3.1.c show two examples of the Base Flow Regime at BDC. Both images are in good agreement with Figure 3.1.a and the vortex structures introduced above are clearly visible.
Figure 3.1: Overview of the Base Flow Regime. a) Schematic diagram of flow regime at BDC: (1) TDC trailing edge vortex; (2) TDC leading edge vortex; (3) BDC leading edge vortex; (4) BDC trailing edge vortex; b) & c) Images of two different flow cases at BDC.
3.1.2 Resonance Flow Regime

The second regime identified has been termed the Resonance Flow Regime. A schematic depiction of the flow as it appears at BDC is shown in Figure 3.2.a. This regime is characterised by a single large vortex that can be seen to form at the nozzle starting at TDC & BDC. In addition, the vortex forms from the trailing edge of the jet (laterally) as the nozzle starts to move away from TDC or BDC. The small vortex previously observed in the Base Flow Regime is no longer visible.

In comparison with the Base Flow Regime, the vortex structures in the Resonance Flow Regime are a lot more regular. Following the formation of the orderly structures, they remain coherent over a distance that is considerably longer than in the Base Flow Regime with very little to no lateral spreading. This is again followed by a region of sudden vortex dissipation. Also, no vortex pairing is visible prior to the dissipation region. This is covered in more detail below.

Figure 3.2.b & 3.2.c show two examples of the Resonance Flow Regime at BDC. Both images are in good agreement with Figure 3.2.a and the vortex structures introduced in the paragraphs above are clearly visible.

3.1.3 Bifurcation Flow Regime

The third and last flow regime identified is termed the Bifurcation Flow Regime. A schematic depiction of the flow at BDC is shown in Figure 3.3.a. This flow regime is characterised by the bifurcation of the vortex structures formed at TDC and BDC of the oscillation cycle. Here the smaller leading edge vortex that is described in the Base Flow Regime does not pair with the larger trailing edge vortex formed at the opposing end of the stroke throughout the time when the vortices are recognisable as coherent structures. Instead, both the leading and the trailing edge vortices generated at BDC and TDC, respectively, form a vortex pair in the shape of a mushroom-like structure. The coherent structures move away from the jet nozzle at a steep angle and generally dissipate rapidly. In most cases the coherent structures are no longer visible after one full cycle.

The Bifurcation Flow Regime was found to mainly exist at flow conditions that included high $S/h$, but also at some conditions with high oscillation frequencies or at a combination of both.
Figure 3.2: Overview of the Resonance Flow Regime. a) Schematic diagram of flow regime at BDC: (1) TDC trailing edge vortex; (2) BDC trailing edge vortex; b) & c) Images of two different flow cases at BDC.
However this is not to say that all flow conditions with large $S/h$ necessarily produced the Bifurcation Flow Regime. Generally this regime develops from the Base Flow Regime when the stroke length is extended or oscillation frequency is increased, but some exceptions exist as is shown below.

At the larger stroke lengths it also appears that the vortex diameters reach a limit for both the leading and trailing edge vortices. Once the stroke length expands beyond this vortex limit a bifurcation is inevitable as the leading edge vortex is laterally removed from the centre flow field.

Figure 3.3.b & 3.3.c show two examples of the Bifurcation Flow Regime at BDC. Both images are in good agreement with Figure 3.3.a and the vortex structures introduced above are clearly visible.

3.1.4 Flow Regime Development

The following section shows how each of the regimes develop over one half of the oscillation cycle. As the coherent structures for all flow regimes were found to be symmetrical across the oscillation centre line, only the half of the oscillation cycle moving the jet nozzle from TDC to BDC is shown here. The images were chosen on the basis that the lateral displacement ($\Delta y$) between each image is roughly equal with a placement error of a maximum of $\pm 7$ degrees. This means that the depicted half-cycle is not necessarily split into equal incremental phase angles in the rotational sense of SHM but in the linear displacement of the jet nozzle moving from TDC to BDC.

The development of flow structures is intrinsically linked to the vertical motion of the plate and related parameters such as velocity and acceleration. Figure 3.4 shows the normalised instantaneous displacement, velocity and acceleration versus oscillation angle for one complete cycle. For better understanding of the following descriptions it is necessary to remember that $\alpha = \pm 90^\circ$ correspond to the jet nozzle passing the oscillation centreline, while $\alpha = 0^\circ$ places the jet nozzle at TDC and $\alpha = 180^\circ$ places it at BDC.

Each panel in Figures 3.5 to 3.8 is split horizontally into two sections. The left hand section
Figure 3.3: Overview of the Bifurcation Flow Regime. a) Schematic diagram of flow regime at BDC: (1) TDC trailing edge vortex; (2) TDC leading edge vortex; (3) BDC leading edge vortex; (4) BDC trailing edge vortex; b) & c) Images of two different flow cases at BDC.
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Figure 3.4: Normalised graph of simple harmonic motion, showing the displacement, velocity and acceleration of one full oscillation cycle.

shows a schematic depiction of the typical flow regime at the instantaneous angle in question, while the right hand side of the panel shows a real example of the respective flow regime recorded during the flow visualisation experiments.

Development of the Base Flow Regime

The individual stages of the development of the coherent large-scale structures in the Base Flow Regime are shown in Figure 3.5.

In Panel a), the jet nozzle is moving upwards towards TDC and decelerating prior to reaching zero velocity at TDC. At this point the large vortex formed on the trailing edge of the jet residing at BDC is nearly fully formed. During the time between Panel a) and b) the jet nozzle has come to an absolute stop and has started moving in the downwards direction towards the oscillation centreline. Over this time the nozzle has undergone its maximum deceleration and acceleration
Figure 3.5: Development of coherent structures for the Base Flow Regime. The right hand side of image panels a) to d) show the actual flow visualisation images for $Re = 1800$, $S/h = 1.0$, $f_o = 1.0Hz$. [(1) TDC trailing edge vortex; (2) TDC leading edge vortex; (3) BDC leading edge vortex; (4) BDC trailing edge vortex]
across TDC as can be seen from Figure 3.4. As the jet decelerates and reaches TDC a small but coherent vortex starts to form from the trailing edge of the jet. As the jet nozzle starts to move again the previous trailing edge now becomes the leading edge and vice versa. While the small leading edge vortex is not yet visible in Panel b), it starts to become fully visible by the time the jet nozzle reaches the phase angle of $TDC + 130^\circ$ in Panel c). Over this time the small leading edge vortex from the previous cycle shown in Panels a) & b) is fully engulfed by the trailing edge vortex from the opposing half of previous cycle relative to itself.

As the flow reaches the angle depicted in Panel c), the formation of the trailing edge vortex becomes visible as well as the formation of the leading edge vortex as it starts to interact with the trailing edge vortex at BDC.

Panel d) shows the full formation of the trailing edge vortex that started to form at TDC and the close interaction between the leading edge vortex with the previous trailing edge vortex from the previous half of the cycle at BDC.

Furthermore, while omitted from Panels a) and b) for clarity reasons, Panels c) and d) show the leading edge vortex from the previous oscillation halfcycle, which moved the jet nozzle from BDC to TDC, interacting with trailing edge vortex of the previous cycle.

**Development of the Resonance Flow Regime**

The individual stages of the development of the coherent large-scale structures for the Resonance Flow Regime are shown in Figure 3.6.

Panels a) to d) are taken at the same oscillation angles as the respective panels in Figure 3.5. The large-scale structures develop similarly to the ones described in the Base Flow Regime but with two major differences.

The leading edge vortices shown to form in the Base Flow Regime are no longer visible. Two possible explanations are offered in this case. One explanation may be that no leading edge vortex is formed in the first place or alternatively, another explanation may be that the leading edge vortex is formed but is engulfed inside the fluid from the trailing edge vortex of the previous oscillation
Figure 3.6: Development of coherent structures for the Resonance Flow Regime. The right hand side of image panels a) to d) show the actual flow visualisation images for $Re = 1800$, $S/h = 1.0$, $f_o = 4.0Hz$. [(1) TDC trailing edge vortex; (2) BDC trailing edge vortex]
halfcycle immediately after leaving the jet nozzle and and hence is not visible.

The other difference noticed throughout all cases of the flow in the Resonance Flow Regime is the much more closer “packing” of the vortices relative to the large-scale structures in the Base Flow Regime. These rows of vortices stay coherent and mostly parallel for a considerable distance without any vortex pairing.

**Development of the Bifurcation Flow Regime**

The individual stages of the development of the coherent large-scale structures for the Bifurcation Flow Regime are shown in Figure 3.7 & 3.8. The flow condition shown here as real images has a large $S/h$, which is where the Bifurcation Flow Regimes seem to be mainly encountered. However, this is not to say that once a certain $S/h$ is exceeded, the large-scale structures automatically exhibit the coherent structure of the Bifurcation Flow Regime. There is clearly a dependence on $U_0$ as well as the $f_o$ in relation to which flow conditions fall into the Bifurcation Flow Regime as is shown in more detail below.

In Panel a), the nozzle is moving upwards and decelerating. It is worth noting that the jet at this point emerges from the nozzle nearly horizontally before deflecting at a significant distance from the plate. The shear layer roll-up on the trailing edge can easily be identified. In Panel b) the nozzle is again moving towards the oscillation centreline while accelerating. By this phase the large-scale structures formed at BDC have nearly fully dissipated and only an incoherent “blob” of dye is visible. However the leading edge of the jet appears to form a hook-like structure together with the trailing edge of the previous half cycle. During the period of time between Panels b) and Figure 3.8.c) this hook-like structure forms into a large-scale vortex along the trailing edge side of the jet. This vortex forms in a similar way to the leading edge vortex encountered in the Base Flow Regime but appears stronger and larger. One possible explanation for this is that this could be due to the fact that the vortex is not engulfed by other high vorticity fluid.

Panel d) shows the flow at BDC. At this phase in the oscillation cycle the trailing edge vortex has also fully formed and, together with the leading edge vortex, forms a mushroom-shaped vortex.
Figure 3.7: Development of coherent structures for the Bifurcation Flow Regime. The right hand side of image panels a) & b) and c) & d) in Figure 3.8 show the actual flow visualisation images for \( Re = 2700, S/h = 5.0, f_o = 1.0\,Hz \). [(1) BDC trailing edge vortex; (2) BDC leading edge vortex; (3) TDC trailing edge vortex; (4) TDC leading edge vortex]
Figure 3.8: Development of the Bifurcation Regime (continued). See previous figure for legend.
structure. At this time also there is no evidence left of a similar vortex structure forming at the opposing end of the oscillation cycle. Further worth noting is the fact that the mushroom structure moves away from the jet centreline at a steep angle. Also at the same time the mushroom structure has surpassed the boundary of the displacement of TDC and has moved outside the oscillation region.

3.1.5 Discussion – Previous Observations and Flow Structure Generation Hypothesis

To the best knowledge of the author, no comprehensive assessment of these flow regimes has been published in the public domain previously. However, two reports have been published previously that provide descriptions that resemble some of these flow features.

As previously discussed in Chapter 1, Fiedler and Korschelt (1979) excited a planar jet in the transverse direction using loudspeakers. They reported the formation of three different flow regimes of which the second regime is of importance for this study as it is shown to have increased entrainment and extensive fluid roll-in. Figure 3.9.a, reproduced from Fiedler and Korschelt (1979), has a strong resemblance to the Resonance Flow Regime. As Fiedler and Korschelt (1979) only varied the frequency of the excitation and not the amplitude of the excitation or the jet velocity, it is not possible to compare the formation of their enhanced mode flow regime directly with the current study. The authors’ main conclusion is that the distance from the nozzle exit to the formation of the large-scale structures shortens with an increase of the oscillation frequency.

The other study to show a flow resembling the current flow regimes is the work documented by Badri Narayanan and Platzer (1989). Figure 3.9.b reproduces the figure from their work relevant to the present study. While again there is some resemblance with the Resonance Flow Regime in so far that only one large-scale vortex is generated at each end of the stroke, some important differences compared with the current study have been found. Firstly, the experimental apparatus

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1This also applies for Iio et al. (2008) shown in Figure 1.18
utilised for their investigation uses a rotational excitation method (Figure 1.19.d) rather than the lateral displacement method as used in the present study, resulting in much more pronounced jet spreading relative to the Resonance Flow Regime. Secondly and contrary to the findings in the present study, the authors describe that the large-scale coherent structures in the flow cases that they investigated, dissipate very rapidly downstream from the nozzle exit.

As a result, no directly relevant explanation of the observed flow regimes is available and hence a hypothesis is formulated to explain the current regimes. All regimes have been shown to generate all of the large-scale flow structures at the extreme displacements of each oscillation stroke, i.e. TDC and BDC. If one is to judge from the flow structure generation of the leading and trailing edge vortices in the Base Flow Regime at these phases in the cycle, the common aspect is the maximum de- and acceleration of the nozzle in the lateral direction. This is similar to what has been described by Pullin and Perry (1980) as a stopping and starting vortex, respectively, and is shown in Figure 3.10.

If this hypothesis is to hold true, the flow must conform to the following chronological events
(described for only one half of the oscillation cycles because the flow is symmetrical): When the nozzle slows down from its upward motion towards TDC, a stopping vortex is created as the nozzle comes momentarily to a rest. This vortex goes on to become the leading edge vortex described in the Base and Bifurcation Flow Regime. As the nozzle starts to accelerate from rest towards BDC, a starting vortex is formed, which becomes the trailing vortex described in all three flow regimes identified in the present study.

While this hypothesis seems plausible and might satisfactorily explain the formation of the large-scale coherent vortex structures, it is not enough to explain the transition from one flow regime to another. This is investigated in the following section.

3.2 Regime Transition in Experimental Flow Visualisation Cases

To further understand the behaviour and transition between regimes of the MOPJ, it is necessary to investigate the changes in conditions between the investigated flow cases. As can be seen from
Table 3.1, a number of trends in respect to flow behaviour become evident.

Upon first investigation, it might be argued that the transition in and out of the Resonance Flow Regime is related to the jet velocity in some way. This can be seen by the movement of the blue shaded area in Table 3.1 towards the bottom right as \( Re_h \) increases. Plotting those flow regimes in a three dimensional grid, as show in Figure 3.11, makes this trend even more evident. It is noteworthy that the Base Flow Regime exists above and below the Resonance Flow Regime at \( Re_h = 1000 \). If this is indicative of the trend at hand, then the same applies for the other Reynolds numbers under investigation, but is outside the tested flow conditions.

Following the conclusions of Galea (1983); Galea and Simmons (1983); Badri Narayanan (1988) and Badri Narayanan and Platzer (1989), who all suggest the use of \( St \) to characterise the flow, i.e. to collapse the data into distinct regimes separated by critical values, one would expect this to be applicable to the data in the present study. However plotting \( St_h \) against \( Re_h \) as shown in Figure 3.12.a does not classify the flow into distinct regimes. This is to be expected as this evaluation completely eliminates any dependence on \( S/h \), which directly contradict observations discussed above. Also from literature reviewed in Chapter 1 such as Badri Narayanan and Platzer (1987a,b) it is clear that the \( S/h \) is of fundamental importance to the separation of flow regimes into various bands or clusters.

This is further supported by general similarity considerations. If one is to consider that the flow regime appears to be dependent on the jet fluid velocity as well as the transverse velocity of the jet nozzle, this can then be written as a ratio of the two velocities at their maximum in the form of

\[
RVel = \frac{|V_{max}|}{U_0} = \frac{2\pi \times f_0 \times S}{U_0} = 2\pi \times St
\]

where

\( RVel \) = Velocity Ratio;

\( 2 \)Due to the coarseness of the experimental data, the individual plots relating \( S/h \) to \( f_0 \) for the various Reynolds numbers have been interpolated by hand. The same applies to Figure 3.15. The interpolation was executed by finding the geometrical mid-points between individual values and then used as field borders.
Table 3.1: Tabulated flow regime classification from flow visualisation experiments.

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Legend:
- \( a \) = Resonant Flow Regime
- \( b \) = Base Flow Regime
- \( c \) = Bifurcation Flow Regime
Figure 3.11: Flow regimes plotted as $f_o$ versus $S/h$ at various $U_0$ in the form of $Re_h$. 
|\(V_{\max}\)| = Maximum Magnitude of the Transverse Nozzle Velocity;

\(U_0\) = Mean Jet Velocity at the Nozzle Exit;

\(f_o\) = Oscillation Frequency;

\(S\) = Stroke Height;

\(St\) = Stouhal number.

By omitting the scaling constant \((2\pi)\) this velocity ratio becomes equal to the Strouhal number defined on the oscillation stroke \((St_S)\). The results of this transformation when applied to the present study against \(Re_h\) is shown in Figure 3.12.b. However from inspection it is evident that this approach is also not successful and does not separate the flow regimes into distinctive bands or regions.

From the observations made from Table 3.1, it is clear that a scaling relationship between \(f_o\) and \(U_0\) \((Re_h)\) exists. Previous studies have shown that changes in \(U_0\) have a direct influence on the natural vortex shedding frequency \((fn)\) in axisymmetric and planar steady jets. When expressed as dimensionless frequency in the form of \(St_n\), this number has been found to be within a very narrow range of \(0.18 \leq St_n \leq 0.24\) over a wide range of Reynolds numbers for smoothly contracting nozzles. A number of investigators such as Oler and Goldschmidt (1984); Everitt and Robins (1978) and Cervantes de Gortari and Goldschmidt (1981) have further reduced this Strouhal number range in their studies and advocate a preferred value of \(St_n = 0.22\). This then means that the natural vortex shedding frequency for the present jet flow can be calculated as

\[
fn = \frac{St_n \times U_0}{h} = \frac{0.22 \times U_0}{h}
\]

(3.2)

where

\(fn\) = Natural oscillation frequency of the planar jet (Hz);

\(St_n\) = Natural Strouhal number of a Planar Jet;

\(U_0\) = Mean nozzle velocity \((m.s^{-1})\);

\(h\) = Nozzle height \((m)\).
Figure 3.12: Plot of $S_{th}$ and $S_{ts}$ versus $Re_h$ by flow regimes.
Figure 3.13 shows the data from the present study in the form of a scatter plot of \( S/h \) versus \( f_o/f_n \) on a \( \log-\log \) scale. This approach separates the individual flow regimes into distinct areas with very few exceptions. Inspecting Figure 3.13 in more detail, the plot can be divided into 4 separate areas as shown in Figure 3.14.

Areas I.a & I.b form the lower and upper boundaries of the Resonance Flow Regime Region, respectively. Area II is the region where nearly all Resonance Flow Regime cases occur and is further bound by Bifurcation Flow Regime boundary line. Area III represents the Bifurcation Flow Regime region.

The transition from any of the regimes to the Bifurcation Flow Regime varies as a functional relationship with \( S/h \) and \( f_o/f_n \). For the present data and \( St_n = 0.22 \), this relationship has been found to follow the equation

\[
\frac{f_o}{f_n} \geq B(S/h) = 3 \times (S/h)^{-2.1}
\]

where \( B(S/h) \) is the critical value of the Bifurcation Flow Regime as a function of \( S/h \).

Figure 3.15 replots the results from Figure 3.11 by non-dimensionalising the oscillation frequency with the natural shedding frequency. In this new figure the regime classification also collapses into their respective areas for all Reynolds numbers investigated with very few exceptions.

This provides further evidence that non-dimensionalising the induced oscillation frequency by the natural shedding frequency is a suitable way to classify the transition between the different flow regimes.

### 3.2.1 Discussion – Transition between Flow Regimes

As discussed in the previous section, none of the three flow regimes found in this study have been described previously by other authors. As such the main focus here is upon the transitions into and out of the Resonance Flow Regime.

Firstly, it is important to note from Figure 3.14 that the Base Flow Regime exists above and below the Resonance Flow Regime in the non-dimensionalised oscillation frequency spectrum. This
Figure 3.13: Flow regimes plotted for $S/h$ vs $f_o/f_n$. 
Figure 3.14: Flow regimes plotted for $S/h$ vs $f_o/f_n$ with regime areas marked-up: I.a: Lower Base Flow Regime Region; I.b: Upper Base Flow Regime Region; II: Resonance Flow Regime Region; III: Bifurcation Flow Regime Region.
Figure 3.15: Flow regimes plotted $f_o/f_n$ versus $S/h$ at various $Re_h$. 
means, for any given $Re_h$ and a constant $S/h < 1.6$, that as the oscillation frequency is gradually increased above a low value (i.e. $f_o/f_n < 0.5$), the flow starts off exhibiting the large-scale coherent structures of the Base Flow Regime and then transforms into the Resonance Flow Regime. As the oscillation frequency is further increased the flow will change back into the Base Flow Regime. This change in flow regimes sees the disappearance of the leading edge vortex followed by its re-emergence, which requires further explanation.

Secondly, closer inspection of Figure 3.14 finds Region II to be centred around a frequency ratio of 1.0 and extends to $0.5 < f_o/f_n < 1.5$. For the actual flow this means that, at $f_o/f_n = 1$, the nozzle is oscillated at or close to the natural shedding frequency and the natural vortex shedding locks on to the excitation frequency.

As was shown for the Base Flow Regime, the leading edge vortex is always smaller and weaker than the trailing edge vortex and at this point any vortex developed due to the deceleration of the jet nozzle is immediately engulfed and absorbed by the previous half cycle trailing edge vortex. This observations supports the argument that within the Resonance Flow Regime, the leading edge vortex does not exist in the first place rather than the alternate hypothesis that it is engulfed very quickly after forming.

This explanation however does not explain why flow conditions with a frequency ratio well above and below the central ratio still exhibit the characteristic structures of the Resonance Flow Regime. Two hypothesis can be offered to address this phenomenon. Firstly, while $St_n = 0.22$ was found to be a typical value from literature, this may not necessarily be the case for the current facility. Allowing for a slight variation in $f_n$, this means the Resonance Flow Regime can be present over a range of non-dimensional frequencies. Secondly, as Putnam (1971) demonstrated extensively in his work, flow structures exhibit the tendency to lock onto preferred flow modes even at Strouhal numbers that deviate somewhat from a central value. Crow and Champange (1971) documented the same observation in their work. While the probability of locking onto a certain mode (in this case the Resonance Flow Regime) reduces with deviation from the central value, it still is probable. This further explains why, even at flow conditions outside Region II in
Table 3.2: Regimes for further PIV investigation at $f = 2.00\,\text{Hz}$. a: Resonance Flow Regime; b: Base Flow Regime; c: Bifurcation Flow Regime.

<table>
<thead>
<tr>
<th>$f$</th>
<th>S/h</th>
<th>Reynolds Number</th>
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<td>1.00</td>
<td>a , b , b</td>
</tr>
<tr>
<td></td>
<td>2.50</td>
<td>c , b , b</td>
</tr>
</tbody>
</table>

Figure 3.14, at a few occasions the flow exhibits all the features of the Resonance Flow Regime as well as a few cases of the Base Flow Regime overlap with the boundary to the Resonance Flow Regime.

3.3 Further Quantitative Investigation

The use of flow visualisation has given rise to a number of hypotheses that seem plausible but require further investigation. For this reason, a few cases in each regime have been chosen for a quantitative study using PIV. Inspection of the Table 3.1 was used to determine the flow cases for this investigation. The final selection was limited to a $f_o = 2.0\,\text{Hz}$ and $S/h \leq 2.5$ as shown in Table 3.2 to ease the process of data collection. As shown, the nine cases earmarked for further investigation span all three flow regimes. As a result cases exceeding $S/h = 2.5$ were not considered for further investigation as the flow separates too easily to be able to collect useful data.

3.4 PIV phase-locked coherent structures

Particle Image Velocimetry data for the flow cases shown in Table 3.2 were acquired to a distance of $x/h \approx 55$ as shown in Appendix H.

Phase-locked PIV data were used to validate the observations made in the qualitative flow visualisation. From each of the three flow regimes, one typical example has been chosen to compare the qualitative with the quantitative experimental data. BDC of each case was further chosen as the most appropriate phase to demonstrate any congruence between the two types of data. For
PIV data collection, the oscillation cycle was split into 20 separate phases and a total of at least 90 images pairs per phase were used to establish a representative data set.

### 3.4.1 Base Flow Regime

Figure 3.16 shows the flow visualisation of the Base Flow Regime example \((Re = 2700, S/h = 0.5, f = 2Hz)\) at BDC. Figure 3.17 shows the same flow phase using PIV data. The flow velocity is normalised by the nozzle exit velocity \(U_0\). The starting vortices in Figure 3.16 can clearly be found in Figure 3.17 at \(x/h = 2.25, 5.75 & 8.0\). To improve the clarity of the velocity vectors, the same flow case is also shown in Figure 3.18, slightly enlarged and without the velocity magnitude in the background. However, both figures do not show the existence of the stopping vortex which, from Section 3.1, one expects to be able to find.

To confirm whether the stopping vortices actually exist or whether they are an artefact of the use of dye in the flow visualisation experiments, one needs to examine the vorticity of the PIV flow field. Vallentine (1969) derives the vorticity of a flow field in the \(x\)-\(y\) plane as

\[
\zeta = \frac{\delta v}{\delta x} - \frac{\delta u}{\delta y}
\]  

(3.4)
Figure 3.17: Phase-locked PIV image at BDC for the flow case $Re = 2700$; $S/h = 0.5$; $f = 2Hz$ showing the normalised vectors and velocity magnitude. All quantities are normalised by $U_0$. 
Coherent large-scale structures are visible at the edges of the jet.
where $\zeta$ is the vorticity in $1/s$. In the cases where the flow is irrotational, $\zeta = 0$. In contrast, if vortices exist in the flow they show up as high magnitude peaks in a vorticity plot. Figure 3.19 shows the vorticity field of the same flow conditions as Figure 3.18. The figure shows areas of high vorticity at $x/h = 2.25, 5.75$ and $8.0$, which correspond to the starting vortices shown in Figure 3.17 and which are congruent with each other (Figure 3.20). Additionally to these areas of high vorticity, Figure 3.19 also shows the existence of another strong vorticity peak at $x/h = 4.0$, pointing towards the existence of another vortex, which corresponds to the stopping vortex closest to the nozzle exit shown in Figure 3.16. Figure 3.21 shows the same plot with the velocity vectors replaced by stream lines. Again, the streamlines marking the starting vortices agree with the vorticity peaks in the plot but not the peaks for the stopping vortices.
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Figure 3.20: Overlay of normalised velocity vectors over the vorticity plot at BDC for flow case $Re = 2700, S'/h = 0.5; f = 2Hz$.

Coherent vortex structures on the outside of the jet flow are visible at locations of high vorticity magnitudes.
Figure 3.21: Streamline plot at BDC for flow case $Re = 2700; S/h = 0.5; f = 2Hz$ superimposed on the vorticity plot. No convection velocity is subtracted. Vortex structures stemming from stopping vortices are not apparent.
A method to visualise the elusive stopping vortices is to subtract the local convection velocity of these vortices from the overall flow field, as has been shown in numerous studies (Perry and Tan, 1984; Perry and Chong, 1987; Powell et al., 1992; Panda et al., 1997).

To find the local convection velocity of the stopping vortex, which formed as the nozzle approaches TDC, a method used by Kelso (1991) is applied here. Using the phase-locked vorticity images of the current flow case, the vortex centre coordinates in successive cycles are traced and plotted as shown in Figure 3.22.a. The distances from the nozzle exit versus time are then curve-fitted and differentiated. This results in a plot of the normalised convection velocity versus normalised downstream distance from the nozzle as shown in Figure 3.22.b), without any large value scatter experienced from differentiating the raw displacement data as shown and discussed by Kelso (1991).

By examination of Figure 3.22.b) a convection velocity of $\approx 0.5 \times U_0$ is found for the TDC stopping vortex at a distance from the nozzle of $x/h = 4$. Figure 3.23 shows the streamline plot superimposed on the vorticity plot after the vortex convection velocity of $0.5U_0$ has been subtracted. This clearly shows a vortex core at $x/h = 4.0$. Furthermore, if the streamlines are superimposed over the velocity vector plot with the vortex convection velocity subtracted (Figure 3.24), a pair of counter-rotating vortices is shown to exist with their respective centres at $x/h = 2.5 \& 4.0$, as is expected from Figure 3.16.

Figure 3.25 combines the three different sets of data discussed previously and traces the large scale flow structures from the flow visualisation image in Panel a) through the PIV velocity plots, both with and without the vortex convection velocity of $0.5U_0$ subtracted in Panels c) and b), respectively.

These figures are confirmation that the large-scale coherent structures found during the analysis of the flow visualisation data for the Base Flow Regime are also found from the quantitative data. Similar results to the one shown for this flow case were also found to exist for the other cases of the Base Flow Regime investigated using PIV.

As an aside point, Figure 3.22.a) clearly shows the convergence of the starting and stopping
Figure 3.22: a): Streamwise and lateral coordinates of the vortex centres for $Re = 2700; S/h = 0.5; f = 2Hz$ using phase locked vorticity plots. b): The normalised convection velocity as a function of total distance of individual large-scale vortices versus distance from the nozzle exit found by differentiation of vortex centre location plots.
Figure 3.23: Streamline plot at BDC for flow case $Re = 2700; S/h = 0.5; f = 2Hz$ superimposed on the vorticity plot. A normalised convection velocity of $0.5U_0$ is subtracted from all velocity components. Vortex structures stemming from stopping vortices are apparent and overlay the high vorticity location. (Shading as in the previous figure.)
A normalised convection velocity of 0.5\(\frac{U_0}{h}\) is subtracted from all velocity components. A counter rotating vortex pair is visible at \(x/h = 3 \pm 0.75\).
vortices for each half of the oscillation cycle, which results in vortex pairing of the two vortices as discussed in the previous sections on this study.

3.4.2 Resonance Flow Regime

The top of Figure 3.26 shows a typical flow visualisation example of the Resonance Flow Regime \((Re = 1000, S/h = 0.5, f = 2Hz)\) at BDC of the oscillation cycle. The bottom of Figure 3.26 shows the normalised velocity vector plot overlaid onto a velocity magnitude plot of the same flow case at the same oscillation phase. Inspection and comparison of the two figures show an excellent agreement between the qualitative and quantitative data.

Both figures show further agreement in another feature. The top of Figure 3.26 shows the onset of the dissipation region after 6 vortices. This is also shown at the bottom of Figure 3.26 and Figure 3.27, which shows the vorticity plot for the same flow condition. The vorticity plot furthermore shows that no other vortices are present for this flow condition, and, as this flow case is a typical example of the Resonance Flow Regime, also in all other cases studied that belong to this flow regime. This is the expected outcome from the flow visualisation. The superimposition of the normalised velocity vector plot over the vorticity plot (Figure 3.28) shows excellent agreement between the two types of data and gives further confidence in the correctness of the observations made so far.

3.4.3 Bifurcation Flow Regime

Figure 3.29 shows a comparison of the flow visualisation image, the velocity plot and the vorticity plot of the Bifurcation Flow Regime for flow case \(Re = 1000, S/h = 2.5, f = 2Hz\) at BDC. Figure 3.30.b then combines the normalised velocity vector plot with the vorticity plot. The two types of data show very good locational agreement. When compared with Figure 3.30.a, it is possible to identify the individual large-scale coherent structures found in the qualitative data with the equivalent structures in the quantitative data. Again, this agreement of structures and locations substantiates all observations made in the flow visualisation section of this study.
Figure 3.25: Tracing of large scale vortex structures from flow visualisation images through normalised velocity vector plots at BDC for flow case $Re = 2700$; $S/h = 0.5$; $f = 2Hz$.  

- a) Flow visualisation image; 
- b) Normalised velocity vector plot; 
- c) Normalised velocity vector plot with $0.5U_0$ subtracted from all velocity components.
Figure 3.26: Comparison of quantitative and qualitative data for a typical example of the Resonance Flow Regime ($Re = 1000$; $S/h = 0.5$; $f = 2Hz$). Top: Phase-locked flow visualisation image of the Resonance Flow Regime at BDC showing large-scale flow structures. Bottom: Plot of the normalised velocity vectors at BDC for the same flow case. Coherent large scale structures are visible at the edges of the jet (All velocities are normalised by $U_0$).
Figure 3.27: Vorticity plot at BDC for $Re = 1000; S/h = 0.5; f = 2Hz$. Zones in red show vortex circulation in the counter-clockwise direction. Blue zones show vortex circulation in the clockwise direction. Six distinct vortex zones can be identified.
Figure 3.28: Overlay of normalised velocity vectors over the vorticity plot at BDC for flow case \( \text{Re} = 1000, \frac{s}{h} = 0.5, f = 2\text{Hz}. \)

Coherent vortex structures on the outside of the jet flow are visible at all locations of high vorticity magnitudes.
Figure 3.29: Comparison of qualitative and quantitative data at BDC of a typical flow case of the Bifurcation Flow Regime ($Re = 1000$; $S/h = 2.5$; $f = 2Hz$). a) Flow visualisation image showing large-scale coherent structures; b) Normalised velocity vector and magnitude plot; (All quantities normalised by $U_0$); c) Vorticity plot. Zones in red show circulation in the counter-clockwise direction. Blue zones show circulation in the clockwise direction.
Figure 3.30: Tracing of large-scale vortex structures from the flow visualisation image through to the normalised velocity vector plots at BDC for flow case $Re = 1000; S/h = 2.5; f = 2Hz$. a) Flow visualisation image. Red dots in circles show approximate centre of the vortex structure; b) Normalised velocity vector plot superimposed on the vorticity plot. Light shaded zones show vortex circulation in the counter-clockwise direction. Dark shaded zones show vortex circulation in the clockwise direction.
3.4.4 Time-averaged Vorticity Data

The previous section presented evidence that the phase-locked vorticity fields of individual flow cases can be used as an appropriate method to perform the flow regime classification in cases where the flow parameters are not known and one has to rely on the appearance of the flow for classification purposes. This visual classification from vorticity data though requires the acquisition of phase-locked data which may not always be available. As a result, it is desirable to utilise time-averaged vorticity data to perform the regime classification.

One case from each of the three flow regimes was selected for further examination as is shown in Figures 3.31 & 3.33. For comparison, the time-averaged vorticity field of the Reynolds number equivalent steady jets are shown in Figure 3.32.

By inspection of the top panel of Figure 3.31, four streaks of high vorticity are clearly visible. The two outer streaks stem from the generation of the starting vortices and their movement downstream over the course of the oscillation cycle. The inner two streaks are in the locations where one would expect to find high vorticity magnitudes stemming from the stopping vortices. This pattern is clearly unique and differs significantly from the steady jet pattern shown in Figure 3.32. The same pattern was found to exist for all Base Flow Regime cases for which quantitative data were acquired.

The bottom panel of Figure 3.31 shows an example of the Resonance Flow Regime vorticity pattern. This pattern only consists of two vorticity streaks as one would expect, as no stopping vortices are evident in the phase-locked flow pattern. This vorticity pattern resembles the pattern of a steady jet more closely but still exhibits significant features that set it apart from a steady jet. Firstly, the vorticity streaks stemming from the starting vortices are broader and significantly shorter than the vorticity streaks resulting from the shear layer vorticity of a steady jet. Secondly, the vorticity streaks do not exhibit the linear growth that is found in the steady jet cases but rather are of constant width. Most importantly though, the vorticity streaks exhibit a region directly

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3In the present study time-averaged quantitative data refer to ensemble-averaged data. Experimental data were only acquired at predefined phases in the oscillation cycle and not in a truly time-averaged manner in the classical sense.
Figure 3.31: Typical normalised time-averaged vorticity plot examples. Top: Base Flow Regime ($Re_h=1800, S/h=0.5, f_o=2$ Hz); Bottom: Resonance Flow Regime ($Re_h=1000, S/h=1.0, f_o=2$ Hz).
Figure 3.32: Normalised vorticity magnitude plots for steady planar jets at $Re_h = 1000$ (top) & $Re_h = 1800$ (bottom).
adjacent to the nozzle exit in which the vorticity streak spreads laterally and in the case shown in 3.31 also exhibit a larger region of vorticity than is found in the steady yet.

Figure 3.33 presents an example of the Bifurcation Flow Regime. This exhibits an entirely different vorticity pattern from the other two flow regimes and the examples of steady jets. In this case four distinct vorticity zones are visible. As the flow is of a bifurcated nature, the vorticity patterns generated by the stopping vortices are in front of the starting vortices. This makes the pattern unique and cannot be confused with either a steady jet vorticity pattern or any of the other two flow regimes described in the present study.

In summary, it has been shown that the flow averaged vorticity patterns can be used to identify the flow regime for a given flow condition. Each of the vorticity patterns has unique features that differentiate them from each other as well as from the vorticity pattern of a steady jet.
3.5 Near field Jet Behaviour & Flow Transition

The previous sections have discussed the initial development of the coherent vortex structures at various phases of the oscillation cycle and have classified the three flow regimes using phase-locked and time-averaged qualitative and quantitative data. The present section shifts the focus to the flow behaviour of the time-averaged jet downstream from the initial formation region and compares it with previous literature.

One of the main characteristics that separate the Base Flow and the Resonance Flow Regimes from other documented oscillating planar jets (with very few exceptions) is the extensive distance from the nozzle for which the large-scale vortex structures remain coherent, undergoing very little transformation and no pairing.\(^4\)\(^5\)

As is shown by a number of examples, the time-averaged Base Flow Regime and Resonance Flow Regime jet cases can be split into three different streamwise regions in the jet near field (Figure 3.34). Closest to the jet nozzle is the initial formation region. In this region the initial large-scale vortex structures are formed. From inspection of the time-averaged jet, this region is characterised by an initially parallel section, which is bound by the jet flow at TDC and BDC in the lateral direction, followed by a spreading region that is the result of the formation of the trailing edge vortices. This formation distance has been found to be at an individually fixed distance for each individual flow case.

Downstream from the formation region is the coherent near field. In this region the jet exhibits extremely low jet spreading and the outside edges of the jet are clearly defined by the coherent vortex structures. In contrast with other jets no vortex pairing or vortex growth occurs here.

On the downstream side, this coherent near field is limited by the transition region. In this region the coherent structures show a sudden break-down of coherent motions and dissipate into small-scale incoherent turbulent motions over a very short distance. Also in this region and further

---

\(^4\)This excludes the pairing of the leading edge vortex with the trailing edge vortex from the previous half-cycle in the Base Flow Regime.

\(^5\)The Bifurcation Flow Regime is excluded from this analysis as a whole as the coherent structures dissipate over a very short distance as demonstrated in the previous sections.
downstream, the jet displays a larger degree of jet spreading compared to the previous region.

3.5.1 Selective Flow Averaging

To present the time-averaged flow from qualitative data in the examples to follow, it is necessary to compile a whole set of images (25 images per cycle for the present study) in a single ensemble-averaged image. However due to the high amount of background colouring, these images have been found to be too dark to allow easy identification of any structures at the outer edges of the jet against the surrounding fluid, even after extensive image manipulation.

As has been shown in the previous sections, all large-scale structures are formed at TDC and BDC. For this reason, a selective averaging process has been chosen to compile the images from a complete oscillation cycle. These averaged images combine the phase-locked images from TDC, BDC and the two images taken at the phase angles when the jet crosses the oscillation centreline. As can be seen in Figure 3.35, the normal averaging process applied in Panel a) is very well represented by using the selective averaging process in Panel b).

This method of selective averaging is more suitable than the normal image averaging method to discuss the time-averaged flow regions and as a result all following qualitative time-averaged images have been processed using the selective method and should be assumed as the applied
averaging method when referred to as time-averaged images in this section.

3.5.2 Near Field Jet Behaviour Overview

Figure 3.36 gives an overview of two typical examples of the Base Flow Regime and the Resonance Flow Regime. Panels a) and b) represent a schematic diagram and real time-averaged image of the Base Flow Regime, respectively. Panels c) and d) present the same for an example of the Resonance Flow Regime. In both, Panels b) and c), the individual regions of the jet flow are clearly visible.

Figures 3.37 & 3.38 depict additional examples of each of the two flow regimes. These examples present further evidence that the three identified flow regions are not unique to the two aforementioned individual cases, but appear to be universal.

Noteworthy is that the coherent near-field region appears to be considerably more pronounced
Figure 3.36: Comparison of schematic overview images with dye flow visualisation. a) Schematic diagram of the combined phase-averaged Base Flow Regime at TDC & BDC; b) Real example of the time-averaged Base Flow Regime ($Re = 1800$, $s/h = 1.0$, $fo = 1.0$ Hertz); c) Schematic diagram of the combined phase-averaged Resonance Flow Regime at TDC & BDC; d) Real example of the time-averaged Resonance Flow Regime ($Re = 1800$, $s/h = 1.0$, $fo = 4.0$ Hertz)
CHAPTER 3. EXPERIMENTAL RESULTS & DISCUSSION

Table 3.3: Comparison of various Base Flow Regime cases and changes to vortex formation distance ($\Delta x_f$) and lateral width ($\Delta y_f$), relative to the reference case in Figure 3.39.

<table>
<thead>
<tr>
<th>$Re_h$</th>
<th>$S/h$</th>
<th>$f_o$</th>
<th>$\Delta x_f$</th>
<th>$\Delta y_f$</th>
<th>Change in condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>1.0</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>Reference</td>
</tr>
<tr>
<td>1800</td>
<td>0.5</td>
<td>2.0</td>
<td>43%</td>
<td>-8%</td>
<td>$0.5 \times S/h$</td>
</tr>
<tr>
<td>1800</td>
<td>1.0</td>
<td>1.0</td>
<td>85%</td>
<td>26%</td>
<td>$0.5 \times f_0$</td>
</tr>
<tr>
<td>2700</td>
<td>1.0</td>
<td>2.0</td>
<td>69%</td>
<td>0%</td>
<td>$1.5 \times Re_h$</td>
</tr>
</tbody>
</table>

and extends further downstream for cases of the Resonance Flow Regime in Figure 3.38 than for cases of the Base Flow Regime in Figure 3.37. This even applies for very similar flow conditions such as shown in Figure 3.37.b in comparison with Figure 3.38.c, in which case $f_o$ is doubled between the two flow cases from 2 Hz to 4 Hz and the remaining flow parameters are held constant.

3.5.3 Flow Variation

Following on from the previous section, insight is sought to explain the variation of the jet spreading in the formation region as well as the formation distance as a function of flow parameters. This is undertaken by comparing an arbitrarily chosen base case with similar cases in which individual flow parameters have been changed in a controlled manner (Figure 3.39, Table 3.3).

The base flow condition is shown in Figure 3.39.a. The flow condition in Panel b) varies from this case by halving the oscillation stroke while keeping the other parameters constant. This results in an elongation of the vortex formation distance ($\Delta x_f$) by 43% but the jet spread remains nearly identical ($\Delta y_f = -8\%$).

In Panel c) the oscillation frequency is halved relative to Panel a). In this case, the vortex formation distance is also extended when compared with the base case ($\Delta x_f = 85\%$) and the jet spreading is increased by $\Delta y_f = 26\%$.

In Panel d) the jet velocity is increased. This also results in a longer formation distance ($\Delta x_f = 69\%$) but the jet spread in the initial formation regions remains approximately constant.

$^6$\(\Delta x_f \) & $\Delta y_f$ are visually estimated from the time-averaged qualitative data and are only used as guidance not absolute values.
Figure 3.37: Different cases of time-averaged flow cases of the Base Flow Regime.
Figure 3.38: Different case of time-averaged flow cases of the Resonance Flow Regime.
Figure 3.39: Comparison of different flow conditions in the Base Flow Regime. a) Nominal case of the Base Flow Regime for comparison purposes; b) Reduction of oscillation stroke against the base case; c) Reduction of the oscillation frequency against the base case; d) Increase of jet velocity against the base case.
The reduction in jet spread shown in Panel b) is to be expected, as the oscillation stroke determines the majority of the jet spread, i.e. an oscillation stroke of $S/h = 2.5$ will always result in a larger jet spread than an oscillation stroke of $S/h = 0.5$, though it is interesting to find that the halving of $S/h$ has only a minor impact on the spreading of the coherent structures. However, the significant change in spread of the coherent large-scale structures in the flow through variation of the excitation frequency suggest that the initial jet spread is dependent on a product of $S/h$ and $f_0$ rather than on $S/h$ alone.

More attention though has also to be paid to the changes in $x_f$. As shown in Table 3.3, any change to the flow parameters has significant impact on $x_f$. An increase of $Re_h$ by 50% increases the formation distance by nearly 70%, while a decrease in $f_0$ by 50% results in an increase of $x_f$ by 85%.

### 3.5.4 Discussion – Time-averaged Results

Comparing the findings from the time-averaged flow results with previous literature leads to a number of important conclusions.

As described in Chapter 1, three distinct flow regions have already been documented by Fiedler and Korschelt (1979). These show general agreement with the current investigation, however with two major differences:

1. Fiedler and Korschelt (1979) describe that the flow exhibits a continuous rate of spread, albeit at a slower rate once the flow reaches the coherent near-field region ($x_a$, Figure 1.16), in contrast to the discovery of close to zero jet spread in the same region for the present study; and

2. Fiedler and Korschelt (1979) claim to observe an onset of noticeable flow excitation only above a minimum oscillation threshold as a product of excitation frequency and oscillation amplitude. Although they used a considerably smaller $S/h = 0.035$ as shown in Table 1.2, this minimum threshold was not observed to exist in the present study.
Badri Narayanan and Platzer (1989) also documented the existence of the same three flow regions in regards to initial formation, coherent near field and sudden dissipation region. Again though, the most notable difference to the present study is also given by a continuous expansion of the jet following the initial vortex formation as shown in Figure 3.9.b. One possible explanation is in the difference in experimental apparatus used by Badri Narayanan and Platzer (1989) compared with the current study. The apparatus used in this earlier investigation is shown in Figure 1.19.d and it imposed a rotational component to the movement of the jet nozzle. This is not the case in the present study due to the lateral movement of the jet nozzle.

A region of sudden breakdown of coherent structures into incoherent, small-scale turbulent motion is also reported by Fiedler and Mensing (1985) during the investigation of the effects of an acoustic excitation on a single shear layer. The authors also found for the onset of sudden dissipation to occur at an individually fixed distance downstream from the nozzle for each flow case.

From the results shown in Figure 3.39 and the related changes to \( x_f \), the findings previously documented by Badri Narayanan and Platzer (1987a); Badri Narayanan (1988) and Badri Narayanan and Platzer (1989), who relate the vortex formation distance to \( St_b \), warrant further investigation using quantitative data.

### 3.6 Vortex Formation Distance

As noted in Chapter 1, Badri Narayanan and Platzer (1987a, 1989) and Badri Narayanan (1988) used a hot-wire probe to measure the onset of vortex roll-up motion and hence the location of \( x_f \) as part of their investigations. Further calculations by the same authors showed that the measured \( x_f \) coincided with a streamwise location at which \( St_b \) was calculated to have a limited number of values between 0.05 and 0.067 for the majority of examined flow cases.

To be able to compare the results of the current study with those of previous studies, a number of assumptions have to made for the acquisition of \( x_f \). Badri Narayanan (1988) wrote that
the lateral distance of the hot-wire probe, $y_p$, was a “few centimetres” away from the oscillation centreline (Figure 1.24). This is not definitive and, as discussed in Chapter 1, the distance of $y_p$ will have some effect on the measured value of $x_f$.

In the present study, the instantaneous velocity was measured at $y/h = \pm 1.0$, i.e. 1 nozzle height above and below the oscillation centreline, to determine the onset of vortex roll-up (Figure 3.40). As has been shown in the results presented in earlier sections of this study, the formation of large-scale vortices is completed at the phase where the oscillation stroke reaches the opposing end of the oscillation cycle. Hence only phase-averaged velocity data of the oscillation cycle at TDC and BDC are used to measure $x_f$. Table 3.4 shows the measured values of $x_f$ and calculated $St_b$ for the current study.

Inspection of Figure 3.41 clearly shows two findings. Plotting $x_f$ against $S/h$ in Figure 3.41.a

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7The jet halfwidth $b$ for the calculation of $St_b$ was found using the steady state PIV data acquired for the calibration of the experimental facility.
Table 3.4: Values of $x_f$ and $St_b$ for the current study using TDC & BDC phase-locked velocity data.

<table>
<thead>
<tr>
<th>$Re_h$</th>
<th>$S/h$</th>
<th>$f$</th>
<th>$x_f/h$</th>
<th>$St_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.5</td>
<td>2 Hz</td>
<td>1.2</td>
<td>0.157</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2 Hz</td>
<td>1.15</td>
<td>0.157</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2 Hz</td>
<td>0.0</td>
<td>0.150</td>
</tr>
<tr>
<td>1800</td>
<td>0.5</td>
<td>2 Hz</td>
<td>1.45</td>
<td>0.093</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2 Hz</td>
<td>1.2</td>
<td>0.091</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2 Hz</td>
<td>0.15</td>
<td>0.084</td>
</tr>
<tr>
<td>2700</td>
<td>0.5</td>
<td>2 Hz</td>
<td>1.3</td>
<td>0.059</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2 Hz</td>
<td>1.2</td>
<td>0.059</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2 Hz</td>
<td>0.35</td>
<td>0.055</td>
</tr>
</tbody>
</table>

Notes: For $x_f = 0, b = h$.

shows that the values of $x_f$ for each Reynolds number are approximately the same at each stroke length and hence suggest that $x_f$ is in fact a function of $S/h$ for a constant $f_o$. At the same time it is apparent that $St_b$ is essentially constant for each stroke length investigated.

Further inspection of Figure 3.41.b shows that $St_b$ varies as a function of $Re_h$ for a constant $f_o$, while $x_f$ does not exhibit a consistent trend in relation to variation in $Re_h$. The change of $St_b$ as a function of $Re_h$ is clearly inconsistent with the finding that $St_b$ is approximately constant made in Badri Narayanan and Platzer (1987a) and Badri Narayanan (1988) and hence requires further examination.

3.6.1 Discussion – Vortex Formation Distance

Figure 3.42 shows the measurements of $St_b$ versus $Re_h$ as presented by Badri Narayanan and Platzer (1987a) and Badri Narayanan (1988). Close examination of these two studies reveals that all data were gathered for $S/h = 1.5$. However no details are provided in either study as to the exact operating used to obtain these data.

Further examination of the results provided in those two studies suggests that $x_f$ is located in the self-similar far-field of the steady jets and hence by substituting Equations 1.2 & 1.3 into $St_b$. 
Figure 3.41: Display of $x_f$ and $S_{th}$ for the present study: a) Plot of data by $S/h$; b) Plot of data by $Re_h$. Lines are to visually connect the data points for each $S/h$. They do not necessarily suggest the shape of the data trend.
it can be shown that

$$S_{tb} = \frac{f_o b}{U_{CL}} = \frac{f_o h}{U_0} \left( \kappa_b^{0.5} b \right) \left( \frac{x - x_o 1}{h} \right)^{0.5} \left( \frac{x - x_o 2}{h} \right)$$

(3.5)

This means that, without knowledge of the correct coefficients for each $Re_h (U_0)$ and also $x_f$ for each data point in Figure 3.42, no definitive comparison is possible between data from the present study with the data of Badri Narayanan and Platzer (1987a) and Badri Narayanan (1988). Thus, we cannot come to any useful conclusions in relation to $x_f$.

However, the apparent discrepancy between the current study and previous studies regarding the dependence of $S_{tb}$ on $Re_h$ can easily be explained by the discussion in the previous paragraphs. In Table 3.4, it can be seen that the measured values of $x_f$ are within the potential core region of the planar steady jet. This means from the definition of $S_{tb}$ that $U_{CL} = U_0$. Also because $f_o$ is held constant for all nine investigated flow cases, one can substitute

$$S_{tb} = \frac{f_o b}{U_{CL}} = \frac{f_o b}{U_0}.$$  

(3.6)

As $b$ has been found to exhibit only very little growth and remains nearly constant for each of the investigated $U_0$ within the region of interest, then $S_{tb} \propto \frac{1}{U_0}$. Using the current methods and definitions of $x_f$, not enough data from previous literature are available to allow for a direct investigation.
of \( x_f \) as a function of \( f_o, U_0 \) and \( S/h \).

In addition there are a number of general problems with the methods by which Fiedler and Korschelt (1979); Badri Narayanan and Platzer (1987a) and Badri Narayanan (1988) acquired data in their studies and in their definition of \( x_f \). From the given information, Fiedler and Korschelt (1979) appear to have used time-averaged smoke flow visualisation images to define and measure \( x_f \). For this method to be successful, one requires relatively low \( U_0 \) to avoid the dissipation of the smoke upstream from \( x_f \). This makes the method not universally applicable and excludes large \( U_0 \) and hence needs to be reconsidered.

Badri Narayanan and Platzer (1987a) and Badri Narayanan (1988) use quantitative data from hot-wire probes to find the locations of \( x_f \) for their experimental conditions. While this method allows for higher \( U_0 \) than the smoke flow visualisation, this method is ambiguous at best for two reasons: Firstly, the lateral placement of the measurement probe \( (y_p) \) will have an impact on \( x_f \) as discussed previously. Secondly, the definition of the change in the hot-wire data to mark the change from a flapping movement into the vortex roll-up motion is also ambiguous and subjective and so cannot be used for the purposes of a general study.

For these reasons a new, unambiguous definition is proposed for the vortex formation distance, termed \( x_v \) from here on to avoid confusion. As vortices form at the extreme ends of the oscillation stoke (TDC & BDC) and the starting vortex is the only common denominator in the three flow regimes presented in this chapter, it is therefore proposed to use the streamwise and lateral location of the vortex core centre of the starting vortices to measure \( x_v \) and \( y_v \), respectively. Here, \( y_v \) represents the lateral distance between the vortex core centres at TDC and BDC as shown in Figure 3.43.

Figure 3.44.a shows the measured values of the locations of the vortex core centres for the flow cases in the present study for which PIV data are available and the averaged data shown in Figure 3.44.b are listed in Table 3.5.

Figure 3.45 shows \( x_v \) and \( y_v \) for different \( Re_h \) by constant \( S/h \). This clearly shows evidence that \( x_v \) increases with an increase in \( Re_h \) and that it decreases with an increase of \( S/h \). However,
Figure 3.43: Proposed measurement locations of the vortex formation distance ($x_v$) in the stream-wise direction and the lateral vortex core centre distance ($y_v$) at TDC & BDC together with the definitions of $x_f$ & $x_a$ as proposed by Fiedler and Korschelt (1979).

Table 3.5: List of measured $x_v$ & $y_v$ in the present study and flow regime classifications.

<table>
<thead>
<tr>
<th>$Re_h$</th>
<th>$S/h$</th>
<th>$f_0/Hz$</th>
<th>$x_v/h$</th>
<th>$y_v/h$</th>
<th>Flow Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.5</td>
<td>2.00</td>
<td>0.82</td>
<td>1.52</td>
<td>Resonance</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2.00</td>
<td>0.57</td>
<td>1.38</td>
<td>Resonance</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.00</td>
<td>0.22</td>
<td>0.45</td>
<td>Bifurcation</td>
</tr>
<tr>
<td>1800</td>
<td>0.5</td>
<td>2.00</td>
<td>1.78</td>
<td>1.88</td>
<td>Base</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2.00</td>
<td>1.38</td>
<td>2.00</td>
<td>Base</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.00</td>
<td>0.86</td>
<td>1.32</td>
<td>Base</td>
</tr>
<tr>
<td>2700</td>
<td>0.5</td>
<td>2.00</td>
<td>2.42</td>
<td>2.10</td>
<td>Base</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2.00</td>
<td>2.03</td>
<td>2.12</td>
<td>Base</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.00</td>
<td>1.93</td>
<td>1.81</td>
<td>Base</td>
</tr>
</tbody>
</table>
Figure 3.44: Location of the vortex core centres: (a) At TDC and BDC respectively for each flow condition; (b) Averaged values with measurement errors. Typical measurement errors are shown for $Re_h = 1800$, $S/h = 1.0$, $f = 2Hz$ in Panel a).
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Figure 3.45: Variation of $x_v$ & $y_v$ versus $Re_h$ for the experimental cases listed in Table 3.5. Typical error values shown for one example each of $x_v$ and $y_v$. Lines are to visually connect the data points for each $S/h$. They do not necessarily suggest the shape of the data trend.

while the same applies for $y_v$ in relation to $Re_h$. $S/h = 0.5$ & 1.0 produce a very similar trend in $y_v$ rather than a distinct separation.

Plotting $x_v$ and $y_v$ versus $S/h$ for constant $Re_h$ (Figure 3.46), it is clearly evident that the vortex formation distance decreases as $S/h$ is increased. Furthermore, $x_v$ is found in three distinct bands that scale with velocity. Trendlines have been fitted to the values of $x_v$ in the form of negative power laws. This type of trendline should be seen as the most appropriate one, as with increasing $S/h$ $x_v$ will eventually asymptote zero but not become negative. On the other end of the scale as $S/h$ decrease to zero, $x_v$ will gradually increase to infinity as the jet transforms from an oscillating jet to a steady jet.

The values of $y_v$, as plotted in Panel b), still show a distinct separation of the values into bands of $Re_h$, although the picture is less clear. The bands for the flow cases at $Re_h = 1800$ &
Figure 3.46: Variation of $x_v$ & $y_v$ versus $S/h$. Trendlines are fitted to Panel a). Lines in Panel b) are to visually connect the data points for each $Re_h$. They do not necessarily suggest the shape of data trend.
Figure 3.47: Variation of $x_v$ versus $S/h$ scaled with $U_0$ with fitted trendlines for the experimental cases listed in Table 3.5.

2700, which represent the case in the Base Flow Regime are grouped considerably closer together than the values for $Re_h = 1000$. The flow case of $Re_h = 1000$ & $S/h = 2.5$ is in the Bifurcation Flow Regime, and exhibits the lowest value of $y_v$ of all the cases. It is also worth noting that the change in $y_f$ between different values of $S/h$ is largest for cases in which different flow regimes are involved, such as the transition from the Resonance to the Bifurcation Flow Regime at $Re_h = 1000$.

Closer examination of the findings in Figure 3.46.a reveal a distinct connection between $x_v$ and both $U_0$ and $S/h$. All three $Re_h$ cases appear to exhibit a similar behavioural trend with respect to $S/h$, namely the gradual decrease of $x_v$ with increases in $S/h$. An attempt to scale $x_v$ with velocity has been made in Figure 3.47 and this shows a collapse of the individual values for $x_v$ into a narrow band of values when compared with Figure 3.46.

As all quantitative data in the present study are acquired for only a single oscillation frequency, it is not possible to make any direct assessment on the behaviour of $x_v$ with changes in $f_o$. However, from Figure 3.47 it can be concluded that for a constant frequency, $x_v$ is a powerlaw function of $S/h$ in the form of

$$x_v(f_o=c) = (a(S/h)^{-b}) \times U_0$$  \hspace{1cm} (3.7)$$

where $a$ and $b$ are constants. At this point in time and with the currently available body of knowledge and data, it is not possible to make any reliable estimates of the values of $a$ and $b$. 

We now reconsider the result of Fiedler and Korschelt (1979), as described in Figure 1.23 in Chapter 1, which documents the change of $x_v$ solely with respect to changes of $f_o$ while keeping the other parameters of $U_0$ and $S/h$ constant. Examination of the same figure also shows that the amplification distance ($x_a$) is a near-constant distance from $x_f$. Using the knowledge acquired from this study, one can reasonably assume that $x_f < x_v < x_a$ as shown in Figure 3.43. This then leads to the following equation for $x_v$ with constant $U_0$ and constant $S/h$

$$x_v = -cf + d \tag{3.8}$$

where $c$ and $d$ are also constants. Combining Equations 3.7 & 3.8 and normalising with $h$ thus yields

$$\frac{x_v}{h} = \phi \left[ \frac{a(S/h)^{-h} \times U_0}{h}, \frac{-cf_o + d}{h} \right] \tag{3.9}$$

Due to the small data set and constant $f_o$ in the present study it is not possible to further quantify the constants $a, b, c$ & $d$. However, Badri Narayanan and Platzer (1989) report a minimum $x_f$ for their facility, and logically one can assume that the same applies for $x_v$. This minimum distance is represented by $d$ in Equation 3.9. Because this minimum $x_v$ has not been reported for all facilities and does not seem to apply to the current facility either, it can be assumed that $d$ may be dependent on the excitation method or facility.

Finally, it is also plausible that $x_v$ is dependent on the formation of large-scale vortex structures in each flow regime, but due to the lack of additional data available at this time, a conclusive answer cannot be supplied.

Referring to Figure 3.47, one final observation can be made. As a result of the single $f_o$ used in the present study for any quantitative data, no attempt has been made to scale $x_v$ with $f_o$. Interestingly though, an addition of $f_o$ to the results in Figure 3.47 may lead to the generation of a Strouhal number in the form of $\frac{x_v f_o}{U_0}$. However, with the currently available data this is not possible and should be considered for future work.
Table 3.6: Centreline velocity decay rates \((k_v)\) in the self-similar jet far-field and location of the virtual origin \((x_0)\) for the steady jet and the MOPJ cases in this study.

<table>
<thead>
<tr>
<th>(Re_h)</th>
<th>(S/h)</th>
<th>(f)</th>
<th>(k_v)</th>
<th>(x_{01})</th>
<th>Flow Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.0</td>
<td>0.0 Hz</td>
<td>0.36</td>
<td>2.66</td>
<td>Steady Jet</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>2.0 Hz</td>
<td>0.77</td>
<td>6.85</td>
<td>Resonance</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2.0 Hz</td>
<td>0.68</td>
<td>4.03</td>
<td>Resonance</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.0 Hz</td>
<td>n/a</td>
<td>n/a</td>
<td>Bifurcation</td>
</tr>
<tr>
<td>1800</td>
<td>0.0</td>
<td>0.0 Hz</td>
<td>0.36</td>
<td>1.44</td>
<td>Steady Jet</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>2.0 Hz</td>
<td>0.93</td>
<td>10.39</td>
<td>Base</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2.0 Hz</td>
<td>0.87</td>
<td>6.63</td>
<td>Base</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.0 Hz</td>
<td>n/a</td>
<td>n/a</td>
<td>Base</td>
</tr>
<tr>
<td>2700</td>
<td>0.0</td>
<td>0.0 Hz</td>
<td>0.36</td>
<td>1.58</td>
<td>Steady Jet</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>2.0 Hz</td>
<td>0.62</td>
<td>4.04</td>
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</tr>
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<td></td>
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<td>2.0 Hz</td>
<td>0.69</td>
<td>4.93</td>
<td>Base</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.0 Hz</td>
<td>2.91</td>
<td>20.1</td>
<td>Base</td>
</tr>
</tbody>
</table>

Notes: n/a = Not Available.

3.7 Velocity Decay in the Time-Averaged Jet Far Field

Figures 3.48 & 3.49 show the centreline velocity decay in the time-averaged transition region of the steady jet\(^8\) and MOPJ for a range of \(Re_h\). Table 3.6 summarises the centreline velocity decay rate \((k_v)\) for the range indicated by trendlines in the aforementioned figures and the location of the virtual origin of the jet \((x_{01})\) for all investigated cases. Figures 3.50 & 3.51 present the same data sorted by \(S/h\).

Out of the three cases with \(S/h = 2.5\), only data points for \(Re_h = 2700\) are shown by plotting \((U_0/U_{CL})^2\) in the aforementioned figures. In Figure 3.51.b, it can be seen that the time-averaged axial centreline velocity of the two other investigated cases with \(S/h = 2.5\) are significantly lower than the instantaneous exit velocity of the jet. This is also presented in Figure 3.52, which plots the normalised velocity magnitudes for the three cases of \(S/h = 2.5\). As a result of the significantly lower \(U_{CL}\), when the data for \(Re_h = 1000 \& 1800\) are plotted as \((U_0/U_{CL})^2\), they are two orders of magnitudes higher than all the other data and hence are omitted from Figures 3.48 to 3.51.a.

\(^8\)For steady jets, the velocity is considered to be self-similar for \(x/h > 10\). True self-similarity of all quantities generally found for \(x/h \geq 50\).
Also, most of the cases investigated show a departure from a linear velocity decay for \( \frac{x}{h} > 23 \). From the findings and discussions in the previous chapter, it is most probable that these changes in velocity decay rate are also related to the same problem of flow confinement by the facility boundaries that are experienced by the steady jets.

### 3.7.1 Discussion - Time-Averaged Velocity Decay Trends

Within the linear region of each flow case, the data in Figures 3.48 & 3.49 show a number of consistent trends. Firstly, as is clearly evident and also expected from previous studies such as Badri Narayanan and Platzer (1987b), Badri Narayanan (1988) and Badri Narayanan and Platzer (1989) that the velocity decay rates in all oscillating jet cases are higher than that of the steady jet cases. Table 3.6 shows that the closest case of \( k_v \) for a MOPJ case is measured as being nearly twice as high as the steady jet equivalent. Secondly, for all of the investigated cases of \( Re_h \), the virtual origins of the self-similar velocity field \( (x_{01}) \) move closer to the nozzle exit with increase in \( \frac{S}{h} \). This is also expected, as the initial centreline velocity of at the nozzle exit decreases as \( \frac{S}{h} \) is increased. The reason for this is that the volume flow rate for a given \( Re_h \) is constant but the fluid is distributed over a larger stroke length \( (\frac{S}{h} = 0 - 2.5) \) and hence the time-averaged centreline velocity is smaller. This results in a faster evolution from the initial velocity profile to a self-similar velocity profile and hence movement of \( x_{01} \) closer to the nozzle exit. Thirdly, while \( x_{01} \) is different for each flow case, for each \( Re_h \) the \( k_v \) values at \( \frac{S}{h} = 0.5 \% 1.0 \) are very similar.

In contrast, inspection of Figure 3.49 shows that \( k_v \) for \( \frac{S}{h} = 2.5 \) is significantly increased for \( Re_h = 2700 \). Considering trends observed so far, it should be assumed that for \( Re_h = 1000 \% 1800 \) and \( \frac{S}{h} = 2.5 \), a similarly high value of \( k_v \) can be expected.

Comparison of these findings with other studies shows that the change in location of the virtual origin was not observed in earlier investigations. There are two main reasons for this. Firstly, as a result of the number of limited cases investigated, Badri Narayanan and Platzer (1987b); Badri Narayanan (1988); Badri Narayanan and Platzer (1989) only report one case each for oscillating nozzle configurations. Secondly, inspection of Galea and Simmons (1983) shows...
Figure 3.48: Normalised centreline velocity decay plots for $Re_h = 1000 \& 1800$ at $f_o = 2Hz$. Data for $S/h = 2.5$ are not plotted in either panel. Straight lines of best fit are plotted for the range of values from which they were derived. Cases with $S/h = 0.0$ represent steady jet cases. Individual Flow Regimes are reported in Table 3.6.
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Figure 3.49: Normalised centreline velocity decay plot for $Re_h = 2700$ & $f_0 = 2Hz$. Straight lines of best fit are plotted for the range of values from which they were derived. Cases with $S/h = 0.0$ represent steady jet cases. Individual Flow Regimes are reported in Table 3.6.
Figure 3.50: Normalised centreline velocity decay plot at $f_o = 2Hz$ for a) $S/h = 0.5$ & b) 1.0. Straight lines of best fit are plotted for the range of values from which they were derived. Cases with $S/h = 0.0$ represent steady jet cases. Individual Flow Regimes are reported in Table 3.6.
Figure 3.51: Normalised centreline velocity decay plot for $S/h = 2.5$: a) Inverse normalisation as proposed by Rajaratnam (1976). Straight lines of best fit are plotted for the range of values from which they were derived. Cases with $S/h = 0.0$ represent steady jet cases. b) General normalisation of the centreline velocity against steady jet exit velocity. Individual Flow Regimes are reported in Table 3.6.
that five different cases have been examined, but only using small stroke/ nozzle height ratios $(S/h = 0.1 - 0.2)$ and hence are not comparable with the present data.

Now considering Figures 3.50 & 3.51, one further trend is clearly visible. Inspection of the figures and Table 3.6 show that the values of $k_v$ depend on $S/h$ rather than on $Re_h$. This leaves the centreline velocity decay lines tightly lying on top of each other for each $S/h$. Considering Figure 3.50, it is most probable that all cases of $S/h = 2.5$ follow a similar trend of overlapping velocity decay lines, but not enough information is available here. This finding of $S/h$ dependent overlapping centreline velocity decays has not been reported previously and the current amount of data is insufficient to claim universal status of the finding. While the trend is certainly present, further data is needed to back up this observation.

In addition to the results discussed above, it is interesting to find in Figure 3.51.b, that the
centreline velocities for individual cases with $S/h = 2.5$ can be significantly lower than the $U_0$ of steady jets. This raises the question of the appropriate normalisation velocity when applied to jet with non-steady initial conditions. Standard practice for a jet exhibiting a top-hat velocity profile at the nozzle exit is to normalise all velocities by $U_0$. In the case of the oscillating jet, the instantaneous jet still has approximately the same exit profile, but the time-averaged profile can differ significantly. For example, in cases of large $S/h$, the time-averaged exit velocity profile will exhibit a double-peak shape rather than a top-hat profile. Due to the SHM, the jet resides for most of the time in the oscillation cycle at the extreme ends of the oscillation stroke. The choice remains as to which normalisation velocity should be considered as the most appropriate to achieve meaningful results. Is it the oscillation centreline velocity at the nozzle exit, the highest measured velocity in the lateral nozzle exit plane or even the highest velocity measured along the oscillation centreline, which as can be seen in Figure 3.51.b, can occur at a considerable distance from the nozzle exit? The investigation of this question is beyond the scope of the present study and has to be answered separately.

During the course of the present investigation, the jet spreading rates of the MOPJ compared to steady jets were also investigated. As was expected from previous investigations discussed in Chapter 1, all cases of MOPJ exhibited larger spreading rates when compared with steady jet spreading rates. However, the available data acquired in the present study is insufficient to find any general trends, and especially in light of the points raised in the previous paragraph, which questions the appropriateness of the instantaneous $U_0$ for normalisation purposes, these results are not discussed here in detail. Further data is also required to successfully perform an in-depth analysis of this subject and is beyond the scope of the present study.

### 3.8 Large-Scale, Frequency-Uncorrelated Flow Oscillation

During the analysis of the flow visualisation data, it was discovered that some of the flow cases experienced large-scale oscillations that were uncorrelated with the MOPJ frequency ($f_o$).
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A set of random examples is shown in Figure 3.53. The left and right hand panel of each flow case present the large-scale oscillation for two images of the same flow. As can be seen, the flow oscillates along the entire flow including the formation, coherent near field and the transition region of the jet.

Figure 3.54 shows five consecutive phases of the same flow case as shown in Figure 3.53.a. The oscillation phase angle between each image is approximately 14°. Again, the large-scale oscillation is clearly evident. The important thing to note from this image sequence is the fact that the images were not acquired over the same continuous oscillation cycle but are phase-spliced and hence the actual phase difference between two consecutive image panels is at least 374°, i.e. one full cycle plus a phase advance of 14°. This means that the oscillation phase angle between the top panel and the bottom panel in Figure 3.54 is at least 1496° (i.e. more than four full oscillation cycles), making the oscillation completely uncorrelated with the mechanically induced excitation.

It is currently not possible to determine what has produced these large-scale, low frequency oscillations in the flow. The flow visualisation data, where the oscillations have been observed, were taken over a number of days and hence are uncorrelated as well. Also, not all flow cases show the oscillation, which changes throughout the data acquisition period of a single day. Care was taken during the experimental campaign to reach equilibrium conditions in the flow after changes in the flow parameters and hence the transient changes exhibited by the flow between experiments are very unlikely to be the cause of these oscillations.

Two more probable causes of these oscillations are that the experimental facility induces the oscillation through some sort of coupling mechanism, due to the geometry of the components downstream from the oscillation nozzle, or alternatively that the oscillations are part of the flow and occur after some form of transient stimulus is reached.

Evidence of the latter cause have been shown throughout this document and also in reference literature such as Crow and Champange (1971) or Putnam (1971), where oscillating flows have been found to “latch” onto certain preferred forcing frequencies. The same may be true in this case, however the currently available evidence is inconclusive in this respect.
Figure 3.53: Different, randomly chosen cases of large-scale uncorrelated flow oscillation between non-consecutive oscillation cycles.
Figure 3.54: Five consecutive phase images from Pseudo Video for flow case $Re = 1000$, $S/h = 1.0$, $f = 2Hz$ (Top to Bottom). A large-scale flow oscillation which is uncorrelated to mechanical oscillation frequency can be seen.
More evidence though is available for the earlier cause. A hypothesis to explain the phenomenon of low-frequency jet oscillations is the possible existence of a Coanda-effect type oscillation, induced by recirculation in the facility. As part of Section 2.7.5 in the previous chapter, it has already been shown that some recirculation is highly likely within the present facility. Studies such as Viets (1975) and Mi et al. (1995) have also shown that the confinement of a jet after a sudden, large expansion can lead to the occurrence of Coanda-effect-related flow oscillations whereby the jet periodically attaches to one or the other side of the expanded section of duct. The existence of this effect is further strengthened by studies by Revuelta et al. (2004) and Rajaratnam (1976), who investigated the existence of Craya-Curtet jets. While the present jet is of a quasi two-dimensional nature, similar principles as described in the two aforementioned studies are also applicable in the present context. However, as mentioned previously, the presently available data are inconclusive in this respect and the phenomenon equires further investigation.