Experimental Three-Dimensional Velocity Data of a Sweeping Jet from a Fluidic Oscillator

F. Ostermann, R. Woszidlo, C.N. Nayeri, and C.O. Paschereit

Hermann-Föttinger-Institut
Technische Universität Berlin

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Introduction

The properties of turbulent jets is focus of ongoing research because it is of importance for several technical applications such as fuel injection and flow control. Recently, spatially oscillating jets (i.e., sweeping jets) emitted from fluidic oscillators have proven to be effective in, for example, mixing enhancement[1], separation control[2], drag reduction[3], and film cooling[4]. Fluidic oscillators are devices that are able to generate spatially and/or temporally oscillating jets without the need of moving parts because the oscillation is solely caused by the internal flow dynamics. However, the driving mechanisms behind the effectiveness of fluidic oscillators have remained unclear because the fundamental jet properties and flow field is unknown. The main reasons for this shortcoming are the requirements for a high spatial and concurrently high temporal resolution for understanding the complex interactions within the three-dimensional flow fields.

The presented data captures the three-dimensional, quasi-time-resolved flow field of a spatially oscillating jet emitted from a fluidic oscillator into a quiescent environment. It was used for analyzing the three-dimensional jet properties, such as jet depth, velocity decay, entrainment, and jet force. It served as a basis for one journal publication[5] and one PhD thesis[6]. Furthermore, a similar dataset has been consulted for validation of CFD studies[7]. The findings derived from this dataset have also formed the basis for the research on sweeping jets interacting with a crossflow (e.g., Ostermann et al.[8]).

The dataset is published in order to offer a basis for future studies on spatially oscillating jets for other researchers and enable a simple access to the data for validation of CFD studies. Furthermore, it is a suitable dataset for testing new data analysis and visualization approaches.

Experimental Setup

Most experimental details are described in the associated publications. Here, only the main facts are summarized and additional details are provided that may be of particular interest when working with the provided data.

The spatially oscillating jet is created by a fluidic oscillator with two feedback channels. The employed geometry of the oscillator is provided along with the presented dataset as a step file (`fluidic_oscillator.STEP`). The geometry is based on a patent by Stouffer and Bower [9]. The flow dynamics inside the oscillator are investigated by Ostermann et al. [10] and Sieber et al. [11]. The outlet nozzle throat of the oscillator is $25 \times 25\,\text{mm}^2$. The oscillator outlet is installed flange to a wall. The supply rate of the oscillator is provided by a massflow controller. The theoretical jet bulk velocity is determined from the supplied massflow $\dot{m}_{supply}$ assuming ambient conditions (i.e., the ambient density ρ_0) and a top-hat velocity profile at the nozzle throat with the outlet area $A_{outlet}(Eq.\ 1)$.

$$U_{bulk} = \frac{\dot{m}_{supply}}{\rho_0 A_{outlet}} \qquad (1)$$

It is important to note that the inertia of the fluid supply chain does not allow for compensating temporal oscillations in the supply rate. Hence, the provided massflow is the time-averaged massflow. Earlier studies revealed that the massflow exiting the nozzle oscillates temporally due to an oscillating counter-pressure.[10] Although these oscillations are small (of the order of 10%), this may cause discrepancies between the dataset and numerical simulations that assume a constant supply rate as a boundary condition at the inlet.

The velocity data is acquired by employing a stereoscopic particle image velocimetry (PIV) system. The PIV system is able to capture the three-dimensional velocities inside a two-dimensional plane at a sampling rate of 6 Hz. A traversing system enables to move the complete PIV system. This allows for acquiring the three-dimensional velocity field plane-by-plane. The employed coordinate system origin is located in the middle of the oscillator outlet throat. The coordinate x is oriented in the streamwise direction and the coordinates x and y span the oscillation plane. Hence, z is oriented normal to the oscillation plane. The acquired data extends approximately 325 mm in the x-direction, 400 mm in the y-direction, and 150 mm in the z-direction. The extent of the volume is quadruplet when considering the symmetry of the flow field, which is explained later. The individually measured planes are parallel to the oscillation plane because this reduced the most erroneous out-of-plane velocity component. The z-direction is sampled by 22 planes. For each plane, up to 6000 flow field snapshots are recorded. Therefore, the acquisition of the three-dimensional flow field resulted in more than four terabytes of data. The snapshots were evaluated using PIVView3C by PIVTec.

The velocity fields are phase-averaged in order to eliminate stochastic noise, compensate for the small PIV sampling rate, and provide a temporal correlation between the individually measured planes. The data is phase-averaged based on a reference signal as suggested and validated by Ostermann et al.[12] for an oscillating flow field of a fluidic oscillator. The reference signal is extracted from simultaneously conducted pressure measurements inside the oscillator. The reference signal is used for identifying the individual oscillation periods. This information is used to assign one phase-angle to each PIV snapshot. All snapshots within a phase-angle window are averaged. The oscillation period is divided into 120 phase-angle windows with a window size of 3 deg. The starting point of the oscillation period is chosen somehow arbitrarily. It is set to zero pressure difference between two pressure taps inside the mixing chamber (i.e., the reference signal). This approximately coincides with the jet leaving the maximum deflection to flip to the opposite side. The phase-averaged pressure difference is provided in the `pressureData.csv` to enable a simplified phase alignment to other studies. The positions of the pressure sensors are marked by small cylinders located at the oscillator wall in `fluidic_oscillator.STEP`.

It is noteworthy that only one quarter of the symmetric flow field is captured and included in the dataset (i.e., $y > 0$ and $z > 0$). The other quarter of the flow field is obtainable by accounting for the symmetry and if necessary the phase-lag between the sides $\Delta\phi = 180°$ (Eq. 2-3).

$$\begin{pmatrix} u(x,-y,z,\phi) \\ v(x,-y,z,\phi) \\ w(x,-y,z,\phi) \end{pmatrix} = \begin{pmatrix} u(x,y,z,\phi+180°) \\ -v(x,y,z,\phi+180°) \\ w(x,y,z,\phi+180°) \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} u(x,y,-z,\phi) \\ v(x,y,-z,\phi) \\ w(x,y,-z,\phi) \end{pmatrix} = \begin{pmatrix} u(x,y,z) \\ v(x,y,z) \\ -w(x,y,z) \end{pmatrix} \tag{3}$$

The measured data overlaps the planes of symmetry (i.e., the x-y-plane at $z = 0$ and the x-z-plane at $y = 0$), which allows for a smooth transition between the measured and mirrored data. This smooth transition may be achieved by a weighted average of the symmetric and original data with a linear transition from only symmetric flow field at z_{min} of the overlap over the same weight at $z = 0$ to only original data at z_{max} of the overlap. The same approach is applicable for the transition in the y-direction.

Data Format

The dataset includes the three-dimensional, quasi-time-resolved velocity field of one scenario. The oscillation frequency is 11.3 Hz at a supply massflow of $m_{supply} = 50\,\mathrm{kg/h}$, which results in the jet bulk velocity of $U_{bulk} = 18.6\,\mathrm{m/s}$. These parameters and other ambient conditions during the measurements are provided in the file `conditions.txt`.

The file `pressureData.csv` contains the pressure difference between two positions inside the oscillator that are marked as small cylinders in the file `fluidic_oscillator.STEP`.

The text file `gridDefinition.txt` provides the dimensions and size of the structured grid. As aforementioned, the coordinate system origin is located in the middle of the oscillator outlet throat. The coordinate x and y span the jet sweeping plane and the coordinate z is oriented normal to the the sweeping plane. It is noteworthy that the grid is not uniformly spaced in the z-direction.

The folder `data` contains the data files. For each phase-angle, one corresponding data file is provided. In total, 120 phase-angles are provided. The name of the files represent the phase-angles in degree. The files are comma-separated UTF-8 data files. Each line, beginning from the second line, contains one velocity vector with its components u, v, and w in m/s at a point x, y, and z in mm. The points are sorted by their coordinate. All points together form the aforementioned structured grid.

It is important to note that the provided precision of the numbers does neither represent the actual precision of the measured velocities nor account for the uncertainty of the PIV measurements. Although the data is provided at a precision of 1/100th of 1 m/s, the PIV measurement uncertainty is expected to be considerably higher. However, the uncertainty has not been quantified because, so far, no reliable nor convenient procedure of quantifying the uncertainty of stereoscopic PIV measurements exist.

Investigating the three-dimensional, quasi-time-resolved flow field requires post-processing tools that are able to handle the amount of data. One quick possibility for a first exploration using ParaView 5.5.0[13] is described in the following:

1. Extract the dataset by using any appropriate extraction tool (e.g., 7zip, gzip).

2. Open one of the csv-files with paraview. It should now parse the file inside a table.

3. Select the table in the *Pipeline Browser* and click *Filters* → *Alphabetical* → *Table To Structured Grid*. Ignore the error messages that may pop up.

4. Inside the *Properties*-window choose `x(mm)` as *X Column*, `y(mm)` as *Y Column*, and `z(mm)` as *Z Column*. Furthermore, enter the grid-size provided in the `gridDefinition.txt` to the *Whole Extent*-text fields.

Whole Extent	0	119
	0	145
	0	21

5. Click on *Apply* if necessary and change the visibility of the new added object to visible in the *Pipeline-Browser*. Now it is save to clear all errors because no new one should pop up.

6. In order to merge the three scalars u, v, and w to a vector, add a calculator filter (*Filters* → *Common* → *Calculator*). In the formula text field enter:

```
u(m/s)*iHat + v(m/s)*jHat + w(m/s)*kHat
```

7. One phase-angle of the data is now successfully added. Consult the ParaView documentation or the multitude of available tutorials for further steps to explore the data.

Recall that only one quarter of the flow field is included in the provided data. The other parts need to be reproduced with Eq. 2-3 using any post-processing tool. Generally, it is recommended to read the data with a post-processing tool of your choice and save the data again in an appropriate binary format because this most likely reduces the loading times significantly.

Another possibility for a more quantitative investigation of the flow field is for example provided by Matlab [14]. The following code snippets imports data from one timestep using Matlab 2017b:

```
% import csv file
data = csvread(fullfile(path_to_files,'000.csv'),1,0);

% reshape to grid using the information from the gridDefinition.txt
x = reshape(data(:,1),[120,146,22]);
y = reshape(data(:,2),[120,146,22]);
z = reshape(data(:,3),[120,146,22]);
u = reshape(data(:,4),[120,146,22]);
v = reshape(data(:,5),[120,146,22]);
w = reshape(data(:,6),[120,146,22]);
```

Of course, the same procedure is also transferable to other programming languages. Note that this code reads the data in `ndgrid`-format. For `meshgrid`-format an additional rearrangement of dimensions is necessary. This code snippet only imports one quarter of the flow field that is captured in the data. The other parts may be obtained following Eq. 2-3.

Associated Publications

The provided data is part of the discussions in following publications:

F. Ostermann, R. Woszidlo, C. N. Nayeri, and C. O. Paschereit. Properties of a sweeping jet emitted from a fluidic oscillator. *Journal of Fluid Mechanics (accepted for publication)*, 2018.

F. Ostermann. Fundamental properties of a spatially oscillating jet emitted by a fluidic oscillator. *Doctoral Thesis at the Technische Universität Berlin*, 2018. doi:10.14279/depositonce-7144.

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