Three Methods of Measuring Velocity of Drops in Flight Using Jetxpert

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Abstract

Velocity measurements of drops-in-flight can include many different definitions. In this paper three common methods will be described and discussed: Measurement of the velocity of drops in full flight, measurement of elapsed time to drop distance of 1mm from drop emergence, and measurement of elapsed time to drop distance of 1mm from firing pulse.

This paper will also include an overview of JetXpert, the machine vision based drop-in-flight measurement system used for all three velocity measurement methods presented.

Introduction

Velocity can be measured and reported in absolute terms (velocity of drops in flight after ejection) and they can be measured and reported in more relative terms (relative to the actuating pulse, or relative to the moment of droplet emergence). No matter which method is used, in order to measure droplet velocity, the droplets must be imaged in-flight at known times.

For this study, a commercially available strobe-based system[1] was used to image the droplets with a triggered digital camera system and high-powered strobe. The images were then analyzed using image analysis software.

System set-up

Combining state-of-the-art strobing technology with powerful ImageXpert software and hardware, JetXpert provides a flexible platform for analyzing print head performance through drop-in-flight visualization and analysis. A conceptual drawing of the system is shown in Figure 1a.

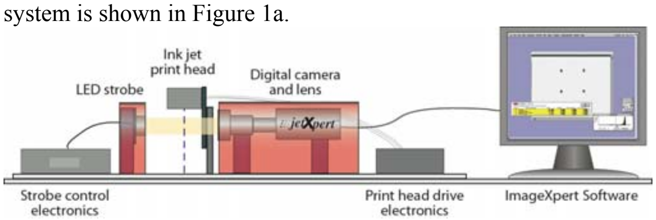


***Figure 1a**. JetXpert system diagram: Strobe, strobe control box, digital camera and lens system, strobe control software and image analysis software*

The strobe was set up to fire once or twice per frame depending on the experiment, enabling imaging of single droplets in each location relative to the print head. This method of image capture minimizes the blur that can be caused by multiple droplet aggregation from multiple strobes (and, therefore, images) per camera frame. Image aggregation is a commonly used imaging method for imaging drops in flight with lower powered strobes, since multiple strobe events are needed to build sufficient image contrast for measurement. By using a high-powered LED, only one single strobe is needed for image capture suitable for analysis. For this experiment, a strobe pulse width of 375ns was used.

Once images were captured, ImageXpert image analysis software was used to perform the analysis based on calibrated droplet distances and strobe delay times. For this setup, the camera had a resolution of approximately 1.7 microns per pixel.

Hardware

The hardware consists of a black and white firewire camera and a special lens system. The illumination source is a custom, high-powered LED strobe that is controlled by proprietary electronics. An image of the image capture hardware is shown in Figure 1b.

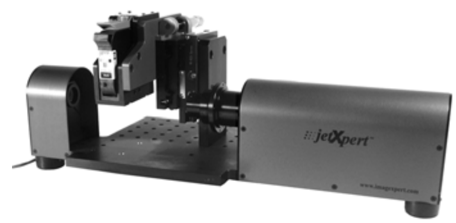


***Figure 1b**. JetXpert system image (showing a HP45 head mounted between the camera and the LED strobe)*

The print head is positioned such that it fires between the camera and strobe so the images of the droplets can be captured in silhouette. If the nozzle plate needs to be imaged for measurement of droplet emergence, for example, the print head needs to be mounted or positioned such that the nozzle plate is in view.

For this experiment, an HP45 ink jet cartridge was used.

Theory of Strobe Operation

In order to synchronize the strobe during print head firing, the strobe is slaved to the print head drive frequency (it can also be triggered via an external frequency generator or an internal clock). The relationship between the firing frequency and the strobe can be controlled via delay settings as shown in Figure 2.

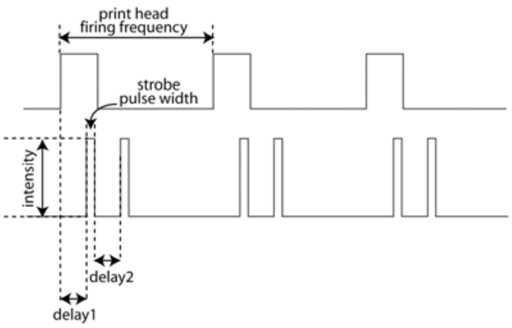


Figure 2. *Diagram illustrating theory of strobe operation*

Delay1 marks the time between the receipt of the firing pulse and the first strobe actuation. The strobe fires for a specific period of time (strobe pulse width) and at a certain brightness (intensity). An optional second strobe can be fired based on the same print head firing pulse. If enabled, delay2 would be the time between the end of the first firing pulse and the beginning of the second pulse. These values are defined and adjusted via the strobe control graphical user interface.

Strobe Control Software

In order to control the strobe itself and define its behavior, certain strobe settings must be defined. The delay between the strobe event and the firing pulse must be defined, and the delay between multiple, sequential pulses must also be defined if a two-drop ("double" drop) option is used for velocity measurement.

Figure 3. *Strobe control dialog box*

The strobe control dialog box allows a user to interactively change strobe settings, apply default analysis and save images interactively. These same capabilities can be used in a more automated way should this system be used for automated inspection rather than interactive use.

Image Analysis Software

The image analysis package used in this system is ImageXpert software. Droplets are identified via a threshold-based algorithm (with dynamic threshold adjustment), and the centroids are calculated. These centroids are used for determining drop position for in-flight analysis, and, depending on the needs of a specific application, the centroid or leading or trailing edge of the droplet can be used for drop "position" determination. For this study, the drop centroid was used.

Velocity Measurement

Three common methods will be described and discussed: Measurement of the velocity of drops in full flight, measurement of elapsed time to drop distance of 1mm from drop emergence, and measurement of elapsed time to drop distance of 1mm from firing pulse.

Velocity of Drops in Full-flight

In this instance, a two-drop ("double" drop) option is used for velocity measurement. A drop is imaged at a certain delay from the firing pulse (delay1), and is imaged again at a later time (delay2). An example is shown in Figure 4a.

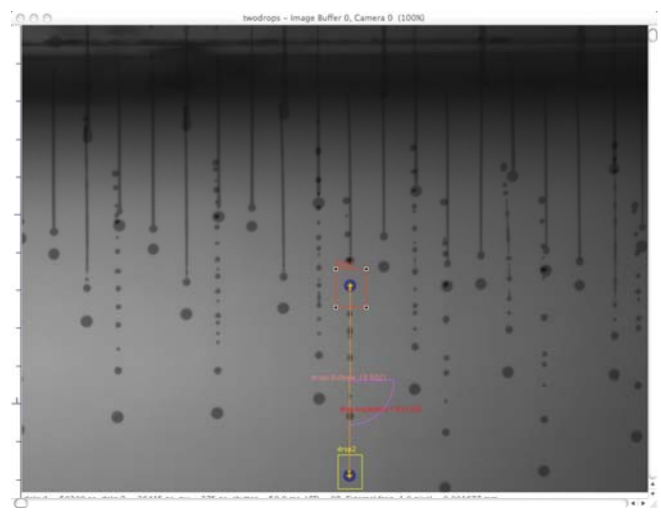


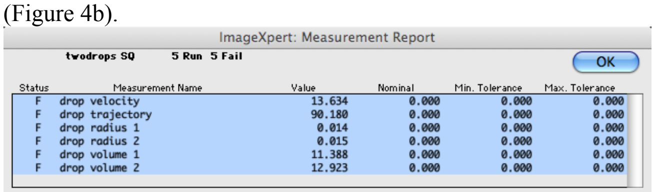
Figure 4a. *Image of double drop for full-flight velocity measurement*

This double drop image allows for measurement of velocity in full flight without needing to know the time of emergence or the back calculation of the time of firing. The time between the two droplet images is known (see Figure 2 for signal information) as shown in equation 1.

$$\text{Time between droplets} = (\text{delay2} - (\text{delay1} + \text{pulse width})) \quad (1)$$

The distance between the two drops is measured using their centroid locations (the system is calibrated and returns results in real world units). The velocity is calculated from the ratio of the distance/time.

In the standard JetXpert system set-up, this full-flight approach is the default velocity measurement method and data is shown on the screen along with droplet volume (picoliter) and trajectory information (degrees), and the data is also saved to a file (Figure 4b).


ImageXpert: Measurement Report

twodrops SQ 5 Run 5 Fail

OK

Status	Measurement Name	Value	Nominal	Min. Tolerance	Max. Tolerance
F	drop velocity	13.634	0.000	0.000	0.000
F	drop trajectory	90.180	0.000	0.000	0.000
F	drop radius 1	0.014	0.000	0.000	0.000
F	drop radius 2	0.015	0.000	0.000	0.000
F	drop volume 1	11.388	0.000	0.000	0.000
F	drop volume 2	12.923	0.000	0.000	0.000

***Figure 4b**.Data from analysis of double drop image for full-flight velocity measurement*

Velocity based on time of emergence

The first step is to determine the difference between the firing pulse and the time of emergence. The value of delay1 is increased until the droplet begins to emerge. That value for delay1 is noted. Then delay1 is increased further until the droplet is 1mm from the faceplate (or some other required distance). The difference in delay times indicates the time for the droplet to travel from emergence to a distance approximately 1mm from the faceplate. Velocity can subsequently be calculated from the ratio of the distance to travel time.

***Figure 5a**. Image of droplet at approximately 1mm from faceplate (0.9389mm)*

The calculation is based on knowledge of the emergence delay (in this case, empirically based on experimentation), and the delay time at ~1mm.

Delay1 at emergence: 6290ns
Delay1 at 0.9389mm = 71540ns
Time difference= 65250ns
Velocity= 0.9389mm/65250ns=> 14.400m/s

Velocity based on time of firing pulse

For this method, delay 1 is simply increased until the droplet is 1mm (or other required distance) from the print head. Velocity can be calculated from the ratio of the distance to the travel time (delay1).

Using the previous example's data:

Delay1 at 0.9389mm = 71540ns
Velocity= 0.9389mm/71540ns=>13.131m/s

Discussion

These three methods are inherently different since each one highlights a different combination of behavior of the droplet firing and flight at a different point in its lifecycle. For some engineers, knowing the time delay between events will be sufficient. To translate these values into velocities may be redundant. For others, it is critical to know the velocity relative to these events—firing pulse or emergence.

For comparison, results from the three methods are tabulated in table 1.

Table 1: Velocity comparison

Sample ID	2-drop velocity (full-flight) (m/s)	From emergence velocity (m/s)	From firing pulse velocity (m/s)
Raw data	13.63385	14.40031	13.13147

Different methods of describing and quantifying droplet behavior might be of interest to different engineers for different reasons. For example, investigating the impact of changing wave forms and voltage on emergence and velocity might be of interest when optimizing system performance and fluid formulation.

Alternatives

There are certainly many other methods for describing and/or calculating the velocity of a droplet than those presented here. For example, a fourth method could be applied for a system using a low firing frequency. A low firing frequency could result in more than one droplet being included in each image frame (simply because it has not moved quickly enough to exit before the next droplet was fired). In this case, using the firing frequency itself and measuring the distance between the first and second drop would be sufficient as inputs for full-flight velocity measurement. This method would not work well with printing systems with higher velocities since the first droplet would have exited the field of view before the second fires.

Another alternative is to measure velocity at different distances from the faceplate since this may be of critical importance to accommodate for the designated throw distance for a given print head or application.

For systems that have a lot of variation in velocity, it is important to collect statistical data instead of single data points to gain insight into true print head behavior. The JetXpert system has the ability to collect statistics during measurement to facilitate this process.

Room for expansion

The basic principals shown here can also be used to help map events (emergence, break off, satellite recombination) on a time line relative to the firing pulse or other "time zero" anchor.

Conclusion

The JetXpert system allows for flexibility in defining and applying measurement methods for investigating behavior of drops in flight. This flexibility is possible using software that allows for changing strobe control (delay times, for example) and software settings to specify distances and drop attributes.

References

[1] Y. Kipman, A strobe-based inspection system for drops-in-flight Proc. SPIE [7242-15] (2009).

Author Biography

Mr. Kipman is the president of ImageXpert Inc., the industry leader in automated machine vision systems for print and process analysis and part inspection. Mr. Kipman founded ImageXpert in 1989. ImageXpert offers a diversified product line that addresses the needs of a wide range of markets including digital printing and related fields. Mr. Kipman holds a M.S. in mechanical engineering, with a major in electro-optics from the University of Connecticut and a B.S. from the Technion Institute of Technology.