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Abstract
A fluidic oscillator is proposed as an improved dynamic calibration device for pressure instrumentation such as pressure-sensitive paint (PSP). The fluidic oscillator is a device that generates an oscillating jet when supplied with a pressurized fluid. The jet oscillation frequency ranges up to 6.5 kHz, depending on supply pressure. The flowfield of the oscillating jet has higher-order frequency content of at least 40 kHz, making it ideal for high-frequency calibrations. The fluidic oscillator demonstrated in these experiments is small, simple to use, portable, and inexpensive. The fluidic oscillator calibration tool may be used to calibrate the frequency response of hot-film or hot-wire probes, as well as pressure instrumentation such as pressure transducers or pressure-sensitive paint (PSP). In this work, the fluidic oscillator is used to calibrate the response time of several PSP formulations. Pressure-sensitive paints with anodized aluminum, polymer/ceramic, and thin-layer chromatography binders are calibrated and compared to previous calibration results. Full-field measurements and point-measurements with PSP are presented. Typical response times of porous PSPs are on the order of 40 kHz.

Introduction
Fluidic Oscillator
Within the realm of aerodynamic testing, there are many situations when unsteady fluctuations dominate the flow. Pressure instrumentation must be able to respond quickly enough in order to accurately resolve unsteady changes in pressure. Thus, there is a need for a response-time calibration tool that can determine the frequency response of pressure instrumentation. Instrumentation such as pressure transducers and pressure-sensitive paint (PSP) need to have their frequency response characterized before they are used in testing. Calibration tools that have been used or are under development include shock tube facilities, solenoid valves, loudspeakers, siren pressure generators, periodic shock wave generators, and pulsating jets. The characteristics of these calibration techniques are summarized in Table 1. These calibration methods have various limitations. Loudspeakers typically have a frequency response on the order of a few hundred kilohertz, but it is difficult to generate pressure waves with large enough amplitude for a useful calibration. Solenoid valves are quite common and can generate a step change in pressure, but are plagued by ringing and a response time that is not fast enough to characterize porous PSP formulations. A supersonic periodic shock generator is capable of generating large pressure changes at high frequencies, but is expensive and difficult to set up. Shock tube facilities are most common for calibrating transducer response, but are not portable or able to be used in the wind tunnel.

The fluidic oscillator is an alternative unsteady calibration tool to these methods. The fluidic oscillator is a small device that generates a fluid jet that oscillates at up to 6.5 kHz when supplied with a pressurized fluid. The oscillator supply pressure ranges from less than 1 psi to over 80 psi. The development history of fluidic oscillators is well documented in published literature. Fluidic oscillators have been used in many diverse applications, such as windshield washer fluid nozzles, cavity resonance tone suppression, flow rate metering, jet thrust vectoring, and enhancement of jet mixing.

There are several distinct advantages to using a fluidic oscillator as an unsteady calibration tool. The fluidic oscillator, as shown in Figure 1, is small, portable, and can be operated from a compressed-air supply. These characteristics make the oscillator easy to use and ideal for on-site calibration of instrumentation in the wind tunnel environment. In addition, the fluidic oscillator costs very little and is easy to fabricate. The oscillator has a large range of operating pressures, and the flowfield contains frequency content ranging up to at least 40 kHz.

Pressure-Sensitive Paint
In these tests, the fluidic oscillator is used to characterize the dynamic response of pressure-sensitive paint. PSP measures surface pressure distributions

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through the processes of luminescence and oxygen quenching. Typically, PSP is illuminated with an excitation light, which causes luminophore molecules in the paint to luminesce. In the presence of oxygen in a test gas, the luminescent intensity of the luminophore is reduced by oxygen molecules from the gas through the process of oxygen quenching. Since the amount of oxygen in air is proportional to pressure, one can obtain static pressure levels from the change in the luminescent intensity of PSP, with intensity being inversely proportional to pressure. Comprehensive reviews of the PSP technique have been published by Bell et al. and Liu et al. Also, Hamner has written a recent paper which serves as a good introduction to pressure-sensitive paint technology.

The PSP formulation traditionally used for conventional testing includes a polymer binder. Conventional polymer-based PSPs are limited in response time, however. The slow response time characteristic of conventional PSP makes it a limited tool in the measurement of unsteady flowfields. Therefore, a fast responding paint, such as porous PSP, is needed for application to unsteady flow.

Porous PSP uses an open, porous matrix as a PSP binder, which improves the oxygen diffusion process. Figure 2 schematically describes the difference between conventional polymer-based PSP and porous PSP. For conventional PSP, oxygen molecules in a test gas need to permeate into the binder layer for oxygen quenching. The process of oxygen permeation in a polymer binder layer produces slow response times for conventional PSP. On the other hand, the luminophore in porous PSP is opened to the test gas so that the oxygen molecules are free to interact with the luminophore. The open binder creates a PSP that responds much more quickly to changes in oxygen concentration, and thus pressure.

There are three main types of porous pressure-sensitive paints currently in use, depending on the type of binder used: Anodized aluminum PSP (AA-PSP) uses anodized aluminum as a porous PSP binder. Thin-layer chromatography PSP (TLC-PSP) uses a commercial porous silica thin-layer chromatography (TLC) plate as the binder. Polymer/ceramic PSP (PC-PSP) uses a porous binder containing hard ceramic particles in a small amount of polymer. For each of these porous surfaces, the luminophore is applied directly by dipping or spraying.

**Fluidic Oscillator Principle of Operation**

The fluidic oscillator operates based on the principle of wall attachment, as shown in Figure 3. When a jet of fluid is adjacent to a wall, entrainment of flow around the jet causes a low-pressure region between the wall and the jet that draws the jet closer to the wall. Thus, the jet will move over until it has attached to the wall. This principle was observed by Henri Coanda in the 1930’s and was later named the Coanda Effect. The Coanda Effect is most commonly encountered in daily life by observing a stream of water from a faucet attach to one’s hand when the two are brought close together. Coanda noticed this phenomenon and applied the principle to steering streams of fluid.

If there are two adjacent walls, such as the symmetric configuration shown in Figure 3, the jet will randomly attach to one wall or the other, based on the randomness of turbulence in the flow. Now, if a pressure pulse is introduced at the control port perpendicular to the jet, the jet will detach from the wall and re-attach to the opposite wall. This occurs through the creation of a separation bubble between the jet and the wall. As more fluid is injected from the control port, the separation bubble enlarges and extends downstream until the jet has entirely separated. The pressure differences and momentum of this separation process then carry the jet over to the opposite wall where it re-attaches.

If the two control ports are set up with a feedback loop system, then the fluidic device can create self-sustained oscillations. A typical design for the fluidic oscillator is shown in Figure 4. At the exit of the oscillator is a lip that directs a portion of the jet into the feedback tube and back to the control port. This feedback flow causes the jet to separate and attach to the other wall. Since both sides of the oscillator have feedback tubes, the jet sustains oscillations.

The rate of jet oscillation depends on many interrelated factors. Most significantly, the length of the feedback tube controls the oscillation frequency. A shorter tube requires less time for the feedback flow to separate the jet from the wall. Therefore, smaller oscillators tend to have higher oscillation frequencies.

**Characterization**

Two different fluidic oscillators are used in the development of the oscillator as an unsteady calibration tool. Both oscillators generate a jet that flips back and forth at a given frequency, and are manufactured by Bowles Fluidics. The first oscillator tested, shown in Figure 1, produces oscillatory flow through the interaction of two jets in an internal mixing chamber. The flowfield of this oscillator is similar to a triangular waveform. The details of operation may be found in Raghu’s patent on the device. The second oscillator tested, also made by Bowles Fluidics, is similar to the type described in Bray’s patent. This second oscillator produces a square wave flowfield.
Raman characterized the flowfield of this exact same oscillator in his paper on cavity tone suppression.22

The first fluidic oscillator, which produces a triangular waveform, has been characterized in previous tests. This oscillator has also been used for preliminary response-time calibrations of pressure-sensitive paint. While the current work involves the square wave oscillator, the previous work is summarized here since the flowfields are similar.

The flow pattern of the Bowles fluidic oscillator used in these experiments is shown in Figure 5. A Schlieren imaging setup is used to record these images. A miniature electret condenser microphone, as seen to the left in the images, is used for triggering the light source for the camera. HFC-134a refrigerant gas is used as a supply fluid, since it can be easily viewed with Schlieren instrumentation. Notice that the jet varies roughly in a sawtooth fashion. These images serve as a useful reference when compared to the images acquired with pressure-sensitive paint.

Pressure-sensitive paint is also used to acquire full-field images of the oscillator flowfield with nitrogen gas. A PSP setup with fast-responding Thin-Layer Chromatography plate PSP (TLC-PSP), as described by Sakaue,40 is used to record the PSP images. A series of two images at separate points in the oscillation cycle is shown in Figure 6. These images correlate well with the Schlieren images of Figure 5.

A hot film probe is used to determine the frequency content of the oscillating jet. The signal from the hot film probe is acquired digitally, and a plot of the power spectrum is generated from the raw signal, as shown in Figure 7. Note that the hot film system used for these measurements has a maximum specified frequency response of 10 kHz. As the oscillator operates at 5 kHz, the flowfield has its primary frequency peak in the power spectrum at 5 kHz. In addition to the primary frequency, there is higher order frequency content in the flow, ranging up to 30 kHz. The high frequency content of the fluidic oscillator flowfield provides a unique opportunity to determine the frequency response of unsteady pressure instrumentation.

A laser scanning system41 has also been used to obtain point measurement results with porous PSP in the fluidic oscillator flowfield.15 The measurement point may be positioned at any point in the jet flowfield. For each point, the PSP signal is acquired, and the power spectrum is generated. This gives an indication of the frequency content of the flowfield and the response characteristics of the porous PSP sample. Figure 8 shows the normalized power spectra generated for all three porous PSP binders studied, at a point near the edge of the oscillatory range of the jet.

All three PSP samples show a frequency response of at least up to 30 kHz. This set of data compares well with the power spectrum generated from the hot film probe signal, shown in Figure 7. Note that AA-PSP has better response characteristics at higher frequency.

One interesting measurement location in the jet flowfield is the frequency-doubled point. This measurement point is located in the center of the jet region, directly below the oscillator exit. This location sees a complete jet passage twice within each cycle. Thus, the jet passage frequency is 10 kHz when the fluidic oscillator is operating at 5 kHz. The laser spot is focused to a diameter of about 0.5 mm, compared to the jet width of approximately 3 mm. At the measurement point, the jet passes completely past the measurement area before returning.

The AA-PSP luminescent signal measured by the photomultiplier tube at the frequency-doubled point is shown in Figure 9. The period of the signal is 100 ms. The average peak-to-peak rise time of the signal is 27.9 ms, which corresponds to a 35.8 kHz frequency response. Peak-to-peak rise times measured for TLC-PSP and PC-PSP are 38.5 ms and 40.6 ms, respectively. These values are averages of the cycle rise times for a data set of over two seconds. The sampling rate of the A/D board is 250 kHz, so the resolution in the rise time measurements is limited to 4 ms.

Note that the waveform is not symmetric in shape, but has a faster rise time than decay time. One possible explanation for this observation is due to fluid mixing. As the jet passes a point on the paint sample, the sharp leading edge of the fluid in the jet creates the fast rise time. On the trailing edge of the jet, however, there is a large amount of mixing between the nitrogen gas in the jet and the surrounding atmosphere. This mixing most likely causes the gradual decay in signal level after jet passage. This hypothesis is supported by examining the Schlieren images of Figure 5. A gradient in the gas density can be seen between the leading edge and the trailing edge of the jet.

Another possible explanation for the asymmetry in the rise time and fall time of the PSP signal is due to the time scale of gas diffusion within the porous binder. There is a finite amount of time required for a gas to fully diffuse through the porous structure. In porous PSP formulations, most of the luminophore molecules are deposited near the surface of the porous structure. Thus, as the paint encounters a step-increase in pressure, the response will be quite rapid. Even though the paint may have responded to the flow change, the process of gas diffusion within the binder may be continuing. Conversely, if the paint sample experiences a step-decrease in pressure, it takes some
time for the high pressure to diffuse back through the porous binder. Therefore, the luminophore molecules on the upper surface continue to sense higher pressures for a longer period of time than the step-increase in pressure. This concept can also account for the delayed signal decay observed in Figure 9.

The power spectrum for the AA-PSP signal at the frequency-doubled point is shown in Figure 10. The primary frequency of this signal is at 10 kHz, with higher order harmonics up to 40 kHz. The power spectra for the signals measured by PC-PSP and TLC-PSP are also shown in Figure 10. Since the power level of the power spectrum plots has been normalized, the relative magnitude of peaks for individual frequencies may be compared between the porous binders. A binder with frequency peaks of lower relative magnitude than the other binders indicates that it has a lower frequency response. When compared to the power spectrum of AA-PSP, the frequency response of TLC-PSP is somewhat lower. TLC-PSP only responds to fluctuations up to 30 kHz. PC-PSP also has a slightly lower frequency response than AA-PSP, but does respond up to 40 kHz. The 40 kHz frequency response of AA-PSP indicated by the power spectrum agrees well with the frequency response measured by the peak-to-peak rise time of the signal (35.8 kHz).

**Dynamic Calibration Results**

In the current work, the square wave fluidic oscillator is operated with compressed air impinging on a PSP sample. These tests demonstrate the utility of the fluidic oscillator as a dynamic calibration device. Two sets of tests are performed. First, the impingement flowfield of the square-wave oscillator is characterized with full-field PSP images. Second, a PSP point measurement is made with three different paint samples. Power spectra generated from the point measurements serve as an indication of the frequency response of the PSP formulations.

**Experimental Setup**

The physical setup of the fluidic oscillator with respect to the paint sample is set for obtaining maximum pressure on the plate, while still allowing optical access to the paint sample. The oscillator and the PSP are mounted on positioning stages to control separation and impingement angles. The oscillator flowfield is set to impinge on the plate at an angle of approximately 15° from normal. The distance from the oscillator to the paint sample is about 2 mm. The oscillator is supplied with compressed air at 40 psi, which causes the jet to oscillate at 2.71 kHz (corresponding to a period of 369 µs).

The pressure-sensitive paint formulations used in these tests are thin-layer chromatography PSP (TLC-PSP), anodized aluminum PSP (AA-PSP), and polymer/ceramic PSP (PC-PSP). All three paint samples use Tris(Bathophenanthroline) Ruthenium Dichloride, (C_{24}H_{16}N_{2})_2RuCl_2 from GFS Chemicals, as the luminophore.

In work with pressure-sensitive paint, there are two forms of instrumentation that may be used for data acquisition. Full-field pressure measurements are performed with a CCD-based system, and point measurements are acquired with a laser-scanning system. Both systems are used in the current tests and are described as follows.

**Full-Field Instrumentation**

The experimental setup for PSP full-field imaging of the fluidic oscillator is shown in the diagram in Figure 11 and the photograph in Figure 12. A 16-bit Photometrics 300 series CCD camera is used for imaging. A 50-mm f/1.8 Nikon lens with a Nikon PK-13 extension tube are mounted on the camera. A 590-nm long pass filter is mounted on the lens for filtering out the excitation light.

A pulsed array of 72 blue LEDs (ISSI model LM2) is used for excitation of the PSP. For full-field imaging, the camera shutter must be left open for an extended period to integrate enough light for quality images. Therefore, the pulsing of the excitation light must be phase-locked with the oscillation of the jet to capture one point in the oscillation cycle. The strobing is phase-locked from the signal of a miniature electret microphone. The microphone signal triggers the gate function on an oscilloscope. The TTL signal from the oscilloscope is fed into a digital delay / pulse generator (Stanford Research Systems DG535) in order to set the phase delay to any point in the oscillation cycle. The pulse generator then drives the LED array, and a pulse counter (Agilent 53131A) is used to count the number of light pulses during an exposure. The pulse width of the excitation light is set at 15 µs, which is 4% of the oscillation period.

**Point-Measurement Instrumentation**

The experimental setup for the PSP point-measurement is shown in the diagram in Figure 13 and the photograph in Figure 14. A 404-nm laser diode (Power Technology LDCU12/5046) is used for PSP excitation. Neutral-density filters are mounted over the aperture of the laser to control the light intensity. A photomultiplier tube (Hamamatsu HC125-01 PMT assembly) is used with focusing optics and a 590-nm long pass filter for collecting the PSP luminescence. The PMT signal is low-pass filtered at 50 kHz and is digitized with a National Instruments DAQ board.
Data Reduction

The PSP signal is then adjusted in slope and offset to a pressure ratio, with respect to atmospheric pressure of 14.15 psi. The PSP signals and the Kulite signals are first corrected by subtracting a dark level image. The camera exposure time is maintained constant for all images (3 seconds for TLC-PSP, 15 seconds for AA-PSP, and 10 seconds for PC-PSP), but the amount of excitation light is not necessarily constant for each image. Therefore, each image is normalized by the number of light pulses that occur while the camera shutter is open. The wind-off reference image is divided by the wind-on images. An a priori calibration in a test chamber is used to generate a second-order polynomial fit to the relationship between intensity ratio and pressure ratio. The calibration is applied to the intensity ratio to obtain pressure ratio, with the reference pressure being 14.15 psi.

Point-Measurement

Once digitized, the PSP and Kulite signals are converted to pressure through an a priori calibration. The PSP signal is then adjusted in slope and offset through an in situ adjustment to match the pressure transducer signal. The pressure signals are converted to a pressure ratio, with respect to atmospheric pressure of 14.15 psi. The PSP signals and the Kulite signals are then digitally high-pass filtered at 100 Hz with a third-order Chebyshev II filter to remove the DC component. The filtering process is performed in forward and reverse on the signal, to cancel any phase shift produced by the filter. The filtered signals are then used to calculate the power spectra with Welch’s averaged, modified periodogram method using a Hanning window of length 4096.

Results

Full-Field

The results from the full-field PSP measurements are detailed in Figure 15. Data from the three paint samples is arranged in the three columns. TLC-PSP results are (a) through (c), AA-PSP results are (d) through (f), and PC-PSP results are (g) through (i). Each row in the figure represents a different time delay within the oscillation cycle. The first row is a delay of 40 μs (ϕ=40°), the second row is a delay of 120 μs (ϕ=117°), and the third row is a delay of 200 μs (ϕ=195°). The oscillator is positioned at the bottom of these images, with the flow exiting the oscillator in an upward direction and impinging on the PSP plate. The vertical dimension of these images has been stretched by 50% for improved clarity. Note that all three paint samples resolve the motion of the jet between the two extremes in its square wave motion. In the time domain, the jet position is mostly at one side or the other, spending very little time in the region between. Also note that the anodized aluminum and polymer/ceramic PSP images are noisier than the thin-layer chromatography PSP. In the case of the AA-PSP, this is due to the age of the paint sample used in these tests (over one year old). The luminophore concentration of the PC-PSP sample prepared for these tests is too low, so the signal level is substantially lower. The magnitude of the pressure fluctuations should not be directly compared between the three paint samples (or with the point-measurement results), because the test geometry is not identical between these cases.

Cross-sectional plots of the PSP samples are generated from a line passing through the maximum pressure in the jet flowfield. These images, shown in Figure 16 through Figure 18, demonstrate the square-wave behavior of the jet oscillation. The lines represent 40 μs steps in the oscillation cycle, ranging from 0° to approximately 195° in phase. Notice the small scale of the flowfield. The range in motion between the two extremes of the jet is only about 2 mm. Also note that the PSP is clearly able to resolve changes within the flowfield between the 40 μs steps.

Point-Measurement

The point-measurement results are the most significant and quantitative results when considering the fluidic oscillator as a dynamic calibration tool for PSP. In an ideal case, the PSP data would be acquired simultaneously with the Kulite pressure transducer at the exact same point in the flowfield. Unfortunately, the laws of physics dictate that two objects cannot be in the same location at the same time. In the case of the fluidic oscillator, the flowfield is fairly small. Even if the Kulite pressure transducer and the PSP laser spot are placed very close together, it would be unreasonable to assume that the two points experience the same pressure at the same instant in time. This difficulty is illustrated by the scale drawing in Figure 19. The diameter of the Kulite pressure transducer is 2.5 mm, and the diameter of the laser spot is approximately 0.5 mm. Due to the size of the Kulite pressure transducer relative to the flowfield, there is
some question as to exactly what portion of the flow the transducer is measuring. The Kulite transducer averages over a larger area than the PSP laser spot.

Instead of attempting to acquire Kulite and PSP signals simultaneously, the data is acquired at the same point in the flow at different times. The laser spot is positioned in the center of the Kulite face. After taking pressure transducer data, the paint sample with flush mounted Kulite is traversed so that the transducer is moved away and PSP is brought into the measurement area. In this manner, time averaged data can be acquired, knowing that both measurements are at the same location in the flowfield. If simultaneous pressure measurements were available at the same point in the flow, then the PSP and Kulite signals could be overlaid and phase delays determined.

The time history of the Kulite pressure transducer is shown in Figure 20. Note that the pressure fluctuations closely approximate the expected square wave behavior. The TLC-PSP measurement at the same location in the flow is shown in Figure 21. Notice that the flow fluctuations are fairly repeatable from cycle to cycle, and that the PSP closely follows the Kulite in rise time. Also notice that the decay time of the PSP signal is slightly than the rise time. This is a similar behavior to the triangle waveform oscillator, shown in Figure 9.

Point measurement data with the laser spot is also used to generate power spectra. By comparing the power spectrum of the PSP signal to the pressure transducer, one can obtain quantitative information about the frequency response of the paint. Within the flowfield of the oscillator, there are two points that the laser spot is positioned for data acquisition. The first point is near the edge of the flowfield where the pressure rise is a maximum. The second point is in the exact center, with respect to the oscillator. This point in the flow experiences the passage of the jet twice within the oscillation period. Thus, the power spectrum will indicate a frequency twice that of the operating frequency. For this reason, this point is referred to as the frequency-doubled point. Both points in the flowfield have higher-order harmonics in addition to the primary frequency. These characteristics of the square-wave oscillator make it ideal for dynamic calibration tests.

Power spectra for the TLC-PSP are shown in Figure 22 and Figure 23, AA-PSP in Figure 24 and Figure 25, and PC-PSP in Figure 26 and Figure 27. All of the power spectra match up well between the pressure transducer and the PSP. In particular, Figure 23 clearly shows frequency content in the TLC-PSP of at least 21 kHz. Any slight differences in the magnitude of the peaks may be attributed to slight misalignments between the PSP laser spot and the Kulite pressure transducer.

Unfortunately, the AA-PSP and PC-PSP samples produced signals that are noisy. Therefore, the noise floor in these power spectra are elevated, such that most of the higher frequency content is lost in the noise. From previous results with the nitrogen-driven fluidic oscillator (Figure 9), it is known that these paint samples have response times of at least 40 kHz.

Future Work

There are several significant aspects of this work that can be improved upon. If a smaller pressure transducer is used, or if the flowfield of the oscillator is enlarged, then simultaneous PSP and Kulite measurements become more feasible. With simultaneous measurements, phase delay data can be obtained by comparing the signals.

The signal-to-noise ratio of the AA-PSP and PC-PSP paint samples must be improved for higher frequency measurements. This can be accomplished by making fresh paint samples.

In the current work the frequency content of the oscillator is not high enough to begin showing the frequency roll-off of the PSP. Therefore, a fluidic oscillator that operates at much higher frequencies must be built. A higher-frequency oscillator, however, is usually smaller in size, thus producing a smaller flowfield.

Bode plots that depict the frequency roll-off of the PSP can be created from the magnitude of the peaks in the power spectrum. This is a analysis technique that was done by Carroll, and can be applied in this case as well.

It is also desirable to independently control the oscillation frequency and the supply pressure. If a flow relief valve is installed on one or both of the feedback tubes to bleed off pressure, then the switching time is increased. Thus, the oscillation frequency can be decreased for a given supply pressure.

Conclusions

The fluidic oscillator has been shown to be an effective unsteady pressure dynamic calibration tool. The oscillator is a small, inexpensive, portable device that covers the frequency and pressure ranges required for most pressure instrumentation. Therefore, the fluidic oscillator serves as an improved unsteady response calibration device. The fluidic oscillator is applied to pressure-sensitive paint instrumentation with an impinging jet of compressed air. The dynamic calibration results clearly show the oscillation of the jet at 2.71 kHz, and the frequency response is at least 40 kHz.
Acknowledgements

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References

## Table 1: Summary of dynamic calibration methods

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![Figure 1: Miniature fluidic oscillator](image1)

![Figure 2: Comparison of porous PSP and conventional PSP](image2)

![Figure 3: Wall attachment in a fluidic amplifier (Coanda Effect)](image3)

![Figure 4: Typical fluidic oscillator design](image4)

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Figure 5: Schlieren images of Bowles fluidic oscillator flowfield at (a) 0° phase and (b) 180° phase

Figure 6: Full-field normalized TLC-PSP images at (a) 0° phase and (b) 180° phase

Figure 7: Normalized power spectrum of the Bowles fluidic oscillator jet, measured by hot film probe

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Figure 10: Normalized power spectra for AA-PSP, PC-PSP, and TLC-PSP at the frequency-doubled point

Figure 11: Diagram of full-field experimental setup

Figure 12: Photograph of full-field experimental setup

Figure 13: Diagram of point-measurement experimental setup

Figure 14: Photograph of point-measurement experimental setup
Figure 15: Full-field PSP data for the oscillator impinging jet. Each paint sample is arranged by columns. TLC-PSP is the first column (a-c), AA-PSP is the second column (d-f), and PC-PSP is the third column (g-i). Each row corresponds to a different phase delay within the oscillation cycle. The first row is a delay of 40 µs ($\phi=40^\circ$), the second row is a delay of 120 µs ($\phi=117^\circ$), and the third row is a delay of 200 µs ($\phi=195^\circ$).
Figure 16: Cross-sectional plot of TLC-PSP full-field measurement

Figure 17: Cross-sectional plot of AA-PSP full-field measurement

Figure 18: Cross-sectional plot of PC-PSP full-field measurement

Figure 19: Relative size of Kulite pressure transducer and laser spot to the oscillating jet flowfield

Figure 20: Kulite pressure measurement

Figure 21: TLC-PSP point measurement at the same point in the flowfield as the Kulite measurement
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Figure 23: TLC-PSP power spectrum, frequency doubled point

Figure 24: AA-PSP power spectrum

Figure 25: AA-PSP power spectrum, frequency doubled point

Figure 26: PC-PSP power spectrum

Figure 27: PC-PSP power spectrum, frequency doubled point