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Engineering Notes

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Noninvasive Measurement of Velocity, Pressure, and Temperature in Unseeded Supersonic Air Vortices

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Introduction

PHYSICAL probes can significantly perturb the flow under study during in situ fluid measurements. Stimulated Raman gain spectroscopy (SRGS) is one of many laser methods under development [1] for a variety of noninvasive diagnostic applications (e.g., use as a database for supersonic wind-tunnel optimization [2]). The SRGS method uses coherent Raman scattering from N_2 in unseeded air and simultaneously produces averaged measurements at a single spatial point of multiple velocity components, along with static pressure and temperature.

In this Note, SRGS measurements are presented that profile offbody flow parameters in the vortex [3,4] of a delta wing (75 deg leading-edge sweepback angle, trailing-edge span of 30.5 cm, and 10 deg beveled leading edge). This work was performed in the Mach 2.8 airflow of the 1.2 by 1.2 m test section of Langley Research Center's Unitary Plan Wind Tunnel (UPWT). Crossing the laser beams achieves a spanwise spatial resolution of 15 mm, which improves upon previous [5] collinear-beam SRGS measurements in the UPWT freestream that obtained only 200 mm spatial resolution. Although this improved spanwise resolution is still somewhat large (10% of semispan) compared with the flow gradients, it is small enough to capture the general features of the vortex for this proof-of-concept demonstration. The sampled point is remotely scanned relative to the model by translating a subportion of the optical system, not including the lasers. Data at several locations along a vertical line, through the core of the vortex, are acquired sequentially. Only one velocity component (spanwise crossflow of the vortex) is measured in the present work.

SRGS Method

SRGS is based on stimulated Raman scattering from a single rotational component ($J = 6$) of a vibrational Q-branch transition ($v = 0$ to $v = 1$) in N_2. Narrow spectral resolution is achieved using two single-mode lasers with frequencies separated by the N_2 vibrational energy of 2230 cm^{-1}. The Raman signal consists of a small fractional power gain generated on the lower-frequency continuous wave (cw) laser beam. Because the signal strength is proportional to the product of the two laser powers, the higher-frequency laser is pulsed to obtain large peak signals.

The experimental setup is shown in the top-view schematic of Fig. 1, which is designed to measure crossflow velocity in the vortex. Freestream velocity, static pressure, and temperature are 630 m/s, 3.3 kPa, and 127 K, respectively. The delta wing angle of attack was 12 deg, and the maximum crossflow velocity in the vortex was equivalent to Mach 1. Two laser beams, a tunable cw 607 nm dye and a pulsed 532 nm Nd:Yag, are directed perpendicularly to the freestream flow direction, focused, and crossed (0.5 deg) at the point of interest in the right-hand vortex above the delta wing. The 532 nm pump beam is stopped by a beam block, and the 607 nm probe beam is retroreflected to cross (0.5 deg) the 532 nm beam a second time in the sample volume and is monitored by a 0.5 ns rise-time photodiode and gated integrators. Crossing of the three laser beams defines an ellipsoid-shaped sample volume at the crossing point in the vortex, where the Raman signal is generated. Sample volume dimensions are about 15 mm (spanwise) by 0.3 mm (vertical) by 0.3 mm (streamwise). Lenses 1 and 2, the retrometer, and other optics (not shown) are mounted on motorized translators so that the SRGS sample volume can be scanned vertically above the delta-wing model without losing the critical overlap of the three laser beams. Thus the SRGS sample volume can be readily moved vertically (with respect to the delta wing) to generate height profiles of the flow parameters through the vortex core.

As the 607 nm laser is tuned over a wavelength interval of 0.2 cm^{-1} (6 GHz), the Raman resonance is observed as stimulated scattering in both the forward and backward directions. The forward signal propagates collinearly along the first 607 nm probe toward the retrometer, whereas the backward signal propagates collinearly along the second 607 nm probe (retroreflected) toward the detector. Because the Q-switched 532 nm laser pulse limits the coherent Raman interaction to 10 ns (10 Hz repetition rate), the backward and forward signal pulses appear at the detector separated by a delay time (25 ns) defined by the separation between the sample volume and the retroreflector. A single measurement requires tuning the laser over the Raman transition ($\approx$30 s) and produces a simultaneous measurement of the forward and backward line shapes.

The forward and backward line-shape data are fit to Voigt line-shape profiles [6] with previously measured low-temperature pressure-broadening coefficients [7]. The $\sim$0.01 cm^{-1} width of the forward line profile (dominated by pressure-broadening) gives the gas pressure, and the $\sim$0.1 cm^{-1} width of the backward line (dominated by Doppler broadening) gives the translational gas temperature. The difference ($\sim$0.02 cm^{-1}) in the Doppler shifts between the forward and backward line centers gives the magnitude and direction of the component of the bulk-flow velocity parallel to the laser beams. In Fig. 1, the crossing angles are small, the laser beams are perpendicular to the freestream direction, and thus the crossflow velocity of the vortex will be measured. Additional details of the experiment can be found in [8], including raw data and fits, UPWT freestream results, a laboratory validation of the SRGS instrument, and a discussion of uncertainties.

Results

Figure 2 shows vertical profiles of crossflow velocity, pressure, and temperature through the core of one of the twin vortices. These

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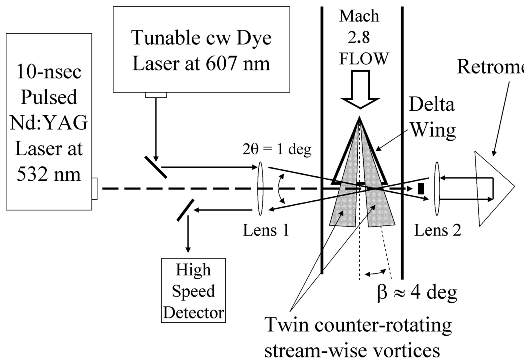

Fig. 1 Top view of the setup used to measure averaged airflow parameters in vortex.

averaged values are determined from limited sets of ≈ six repeated 30 s measurements (made over ≈15 min). The abscissa specifies the height above the delta wing surface of each measurement. The streamwise location of these measurements is 25 mm upstream of the trailing edge. Crossflow velocity data show a direction reversal at 28 mm above the surface. Temperature and pressure values are minimum at 24 mm above the surface and increase in either direction, toward or away from the surface. At the position nearest the surface, the increases in temperature and pressure, accompanied by a decrease in velocity, occur as the flow is heated and slowed in the boundary layer. The data of Fig. 2 roughly illustrate qualitative features expected in a vertical profile through a vortex. Deviations of this SRGS data from the expected vortex features [9,10] may be attributed to spatial averaging over 1.5 cm in the spanwise dimension. The important aspect of this work is the unseeded nature of this offbody flow diagnostic demonstration.

A dashed doubled-headed arrow at ≈17 mm indicates the expected center of the vortex, determined from a five-hole pitot-probe survey (unpublished) that was made before the present work. The probe was also used as a guide for positioning the SRGS sample points in the vortex. The SRGS results were obtained after the probe was backed away from the model, far downstream of the trailing edge of the delta wing. The observed vortex center from the SRGS measurements (distance ≈28 mm where cross velocity ≈0) is displaced from the expected location by about 11 mm. One probable contribution to this 11 mm offset is that the SRGS instrument measures the spanwise velocity component and the vortex axis is tilted at $\beta \approx 4$ deg from the streamwise direction (Fig. 1). Thus, the vertical profile of Fig. 2 will contain an approximate $-630\sin(4\ \mathrm{deg}) = -44\ \mathrm{m/s}$ offset, which will move the zero crossing vertically upward from the surface and explains about 50% of the 11 mm difference. Additionally, any jetlike behavior in the core of the vortex would increase the streamwise velocity and this offset estimate. A second possibility for part of this 11 mm difference is that the probe may move the transverse vortex location, depending on the probe position. The probe tip was positioned at the trailing edge to make the probe survey and positioned far downstream of the trailing edge to make the present SRGS measurements. This speculative interpretation (discussed further in [8]) is consistent with other work, where a similar observation [10] of a probe perturbation of the vortex transverse position was reported in a subsonic study, comparing probe and laser Doppler velocimetry data.

The random errors (precision) in the present averaged measurements are about ± 10 K, ± 0.1 kPa(± 0.001 atm), and ± 10 m/s for temperature, pressure, and velocity, respectively. These are $\pm$ 1 standard deviation (SD) of the mean (at the 68% confidence level), determined from ≈ six measurements. The precision associated with a single measurement (i.e., SD of the sample of six measurements) is $\sqrt{6}$ larger than the uncertainties in the preceding means. For comparison, the single-measurement error computed from the nonlinear fit to the Raman line shapes is typically the same as the SD of the samples. These precisions for the vortex data are consistent with the precisions found in the UPWT freestream or laboratory gas-cell data [8].

Confidence in the accuracy of the measurements of all three vortex parameters comes from these same freestream and laboratory measurements, where the gas parameters are known and show agreement with the SRGS data. The residual differences are upper limits for the systematic errors and discussed in [8]. For velocity, errors in the angle measurements with respect to the flow are estimated (based on beam sizes) at ± 0.5 deg and correspond to ± 5 m/s. AC Stark shifts for the forward line are estimated to be 12 MHz (0.0004 cm^{-1}) for our 40 mJ/pulse 532 nm beam and correspond to ± 5 m/s. Because both forward and backward line shapes are acquired with the same laser power, the Stark error in the difference of the forward and backward Doppler shifts will be less than the ± 5 m/s estimate (both Stark shifts are in the same direction). Adding linearly, the total systematic velocity error from both contributions is estimated to be less than ± 10 m/s. For pressure measurement from the forward line, the error from Stark broadening is typically ≈7% of the width. Generally, in Fig. 2, random errors dominate over the expected systematic errors.

The raw Raman spectra, from which these results are derived, have signal-to-noise ratios (SNR) that are smaller than the largest possible SNR and limited by the amplitude noise of the probe laser. The primary impediment to optimum SNR is floor vibration in the UPWT test-cell environment, which moves the probe beam on the optical detector. This generates excess amplitude noise on the detected 607 nm probe laser intensity and SRGS signal. Flow facilities with milder vibration environments than encountered at UPWT would offer the opportunity for smaller random uncertainties than those quoted previously.

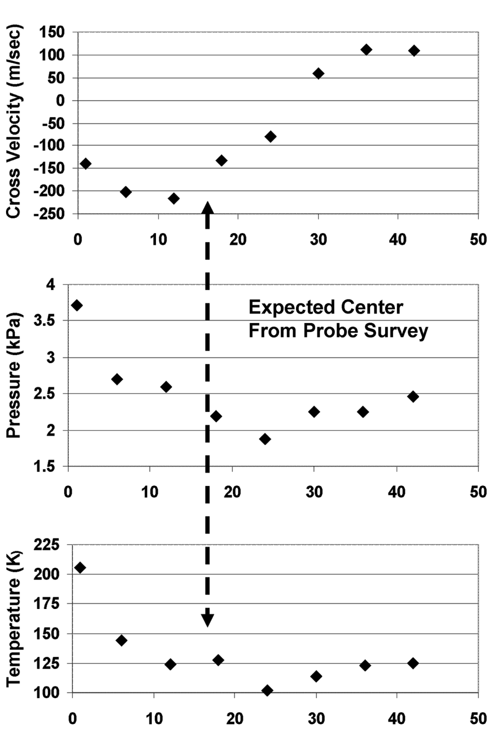

Fig. 2 Vertical profiles of simultaneously measured crossflow velocity, static pressure, and temperature.

Conclusions

In summary, novel nonintrusive time-averaged point measurements of velocity, pressure, and temperature have been demonstrated with vertical height profiles through the low-density vortex core from a supersonic delta wing. The present work illustrates the potential of the SRGS laser diagnostic for noninvasive and quantitative offbody flow measurements for many applications such as vortex and other flowfield studies, wind-tunnel optimization, and validation of computational fluid dynamics.

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