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Analysis of Particle Image Velocimetry (PIV) Data for Acoustic Velocity Measurements

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Abstract

Acoustic velocity measurements were taken using Particle Image Velocimetry (PIV) in a Normal Incidence Tube configuration at various frequency, phase, and amplitude levels. This report presents the results of the PIV analysis and data reduction portions of the test and details the processing that was done. Estimates of lower measurement sensitivity levels were determined based on PIV image quality, correlation, and noise level parameters used in the test. Comparison of measurement results with linear acoustic theory are presented. The onset of nonlinear, harmonic frequency acoustic levels were also studied for various decibel and frequency levels ranging from 90 to 132 dB and 500 to 3000 Hz, respectively.

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Introduction

Measurements were taken of acoustic velocities using Particle Image Velocimetry (PIV) as part of the Advanced Subsonic Technology (AST) program at Langley Research Center. A normal incidence tube configuration was used to set up standing wave acoustic fields which were examined using PIV. The PIV technique, which is typically used to study global velocities in aerodynamic and fluid dynamic flows at Langley, was used to measure acoustically driven displacements on the order of 1-50 microns. The technique will be further refined to measure global acoustic displacement levels in advanced acoustic liner concepts for flow enhancement and noise reduction research efforts.

Normal Incidence Tube (NIT) Theory/Description

In order to test the feasibility of making acoustic velocity measurements with the PIV technique, a series of tests were conducted using an acoustic chamber in a normal incidence configuration. In such a configuration, an acoustic driver is placed at one end of the test cell and a solid wall is placed at the other. The normal incidence tube design provides stationary and well behaved acoustic standing waves according to the equations:

$$u(x) = \frac{-i}{\rho c} \left[|P(L)| e^{-ikL} \sin(k(L-x)) \right] \quad (1)$$

$$\xi(x) = \frac{-i}{\omega} u(x) \quad (2)$$

$$|P(L)| = P_0 10^{(SPL/20)} \quad (3)$$

where $u(x)$ is the displacement induced by the acoustic field, ρ is the gas density, c is the speed of sound, $\omega = 2\pi f$, f is the frequency, k is the wavenumber (ω/c), $P(L)$ is the rms pressure at L , P_0 is the reference pressure of $20\mu\text{Pa}$, SPL is the measured sound pressure level in dB in the chamber, and the $e^{+i\omega t}$ sign convention is being used. A vibrating displacement field is set up under these conditions representing a sinusoidally varying standing wave pattern along the tube length. This situation is depicted in figure 1.

Particle Image Velocimetry (PIV) System Description

Particle Image Velocimetry (PIV) is a non-intrusive global velocimetry/displacement measurement technique that is well established.¹ The technique typically uses a double pulsed

light sheet configuration to illuminate a seeded flow field of interest. Insertion of a precise time delay between the two laser pulses produces temporally displaced particle images that can be recorded on photographic or digital recording media. The temporally displaced particle images are recorded as pairs of images, which can be exploited using image correlation techniques to evaluate localized mean displacement/velocity levels in the flow with measurement accuracies approaching 1% and measurement scales on the order of 1mm^2 .

PIV measurement sensitivity levels are determined and limited by a number of system parameters related to the imaging, laser illumination, seed, and data reduction techniques used. The accurate measurement of acoustic displacement levels on the order of 1 micron in this test required refinements of the existing Langley PIV system.^{2,3} In particular, near-diffraction limited imaging, synchronized (conditionally sampled) phase laser illumination, specialized seeding, and enhanced data analysis and validation schemes were developed and implemented in this effort.

The acquisition system used in this test is depicted in figure 2. Two 580mj YAG lasers were synchronized with the acoustic driver system, and provided light sheets 1mm thick by 50 mm wide. Images of 2.3 micron hollow silica microsphere seed were captured using a near-diffraction limited imaging system, and a Kodak Megaplug 1.4 digital camera system. An approximate 1:1 magnification level was used which provided for an approximate 7.23mm x 5.78mm field of view. Images were captured and transferred in binary 8-bit format using custom interface and control software at a rate of approximately 7 images per minute.

PIV Analysis Process

A custom and automated PIV analysis system was used in this effort based on a PC/AT 486/120 platform incorporating an Alacron/i860 array processing system. The system is currently capable of processing 5 autocorrelation displacement measurements per second, and completes an entire image field in 1 minute with 50% oversampling. A 128x128 pixel correlation size was used to provide the needed accuracy levels. This translates to an approximate 0.7232mm spatial resolution capability, and a 0.3616mm measurement resolution size. Near-diffraction limited image sizes ranged from 4-15 microns which covered 1-4 pixels on the digital camera. This, along with excellent seed density levels of 10-30 image pairs per mm^2 , resulted in correlation signals with SNR in excess of 100:1. A weighted mean centroiding scheme was used, and provided measurement sensitivity levels of 0.01 to 0.1 pixels, which corresponds to a lower limit of approximately 0.2 to 0.3 microns.

PIV Data Validation

Data validation and post processing efforts also involved using custom and automated algorithms based on a PC/AT 486/120 computer platform. Measurement validation rates in

excess of 99% percent were achieved based primarily upon the high image quality available in the raw data. A four-tiered validation routine was used to reduce the analyzed data. This involved a bandpass validator operation, followed by a local median validator, a 3x3 local mean filter, and finally an image shift subtraction operation. The validation process was automated, relying only minimally on operator input, and took approximately 1 second per analyzed data file. Following data validation, the ensemble mean/standard deviation, and data convergence algorithms were applied to the various data sets.

Results

Preliminary data convergence tests indicated an ensemble file number of 20 files to be adequate for this preliminary phase of testing. A 500 Hz driver signal was studied first at increasing decibel levels. Figures 3 and 4 show the results of these measurements. Ensemble average values were obtained for each condition at each position of the flow. This represented a 19x15 grid of spatially resolved displacement measurements for each condition. The mean and standard deviation of the 19x15 grid values were then computed and are plotted in figures 3 and 4. Theory predicts a log₁₀ increase in relative displacement for increasing decibel level which is shown in the log₁₀ plot of figure 4. A 6 dB increase effectively doubled the relative displacement which agrees well with theory. This onset of harmonic frequency, and nonlinear influences was expected at decibel levels above approximately 125 dB for 500 Hz, but no deviation away from the linear fit was seen up to 132 dB levels.

A study of the phase dependence of the signal level was also done for 500 Hz, the results of which are shown in figure 5. In this study the laser pulse separation timing was set to 1/2 the wavelength of the driving function or $1/2 * 1/500\text{Hz} = 1/2 * 2\text{ms} = 1\text{ms}$. This ensured maximum displacement levels for all measurements. The relative phase of the driver and laser pulsing systems were then varied at 1/16th wave increments (0.125ms). As expected, the sinusoidally varying driver function resulted in a sinusoidally varying displacement trace with a phase shift introduced by the speaker driver system. A sinusoidal fit to the data showed a Chi² value of 0.11959. An additional set of phase dependence data was analyzed for 1500 and 3000 Hz driver frequencies at 118 dB each. These results are shown in figures 6 and 7. Theory predicts an inverse relationship between driving frequency and displacement amount which agrees well with the results. A doubling in frequency effectively halved the amount of vibratory displacement. The relative phases are also seen to be in synchronization with the driving frequency for both cases.

Summary

Over 1500 Particle Image Velocimetry (PIV) images were analyzed as part of a NASA Langley effort make acoustic displacement measurements. To test the feasibility of the technique,

a series of measurements were taken in a Normal Incidence Tube (NIT) configuration at frequencies between 500 Hz and 3000 Hz, and decibel levels from 90 dB to 132 dB. Custom PIV analysis algorithms were developed and implemented in the test for data analysis, validation, and post processing efforts. Estimates of measurement sensitivity were also made based on image quality, data convergence, and ensemble statistic evaluations. Several examples of the amplitude, frequency and phase dependencies of the standing wave patterns were presented.

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- [3] Lourenco L., and Krothapalli, A., "On the Accuracy of Velocity and Vorticity Measurements with PIV," *Experiments in Fluids*, 18, 421-428 (1995).

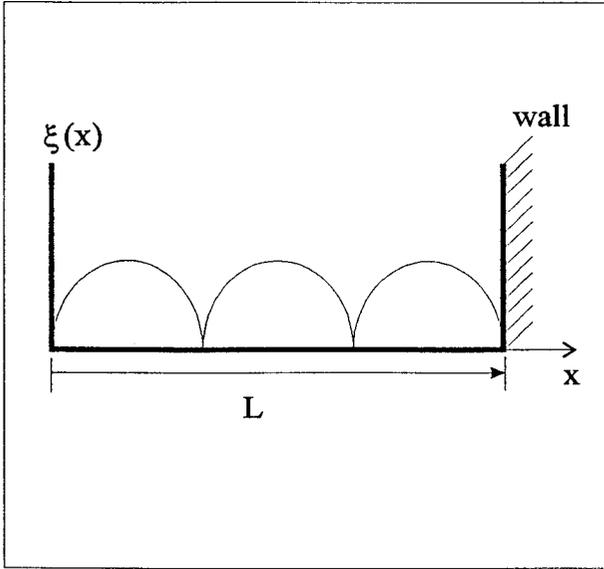


Figure 1. Acoustic Field incident on hardwall.

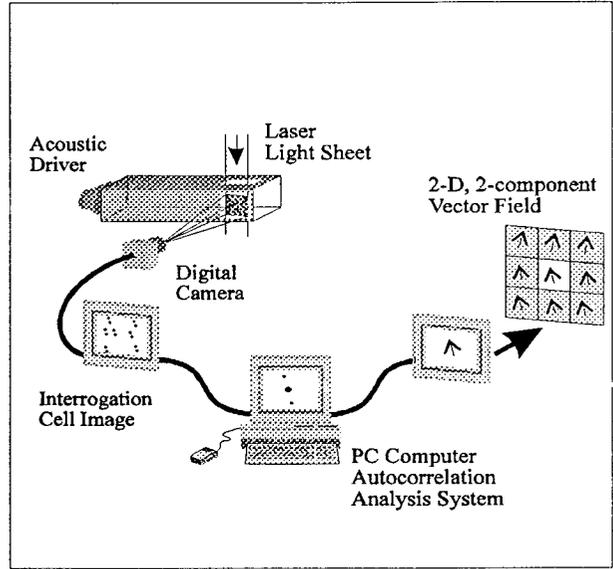


Figure 2. Experiment layout.

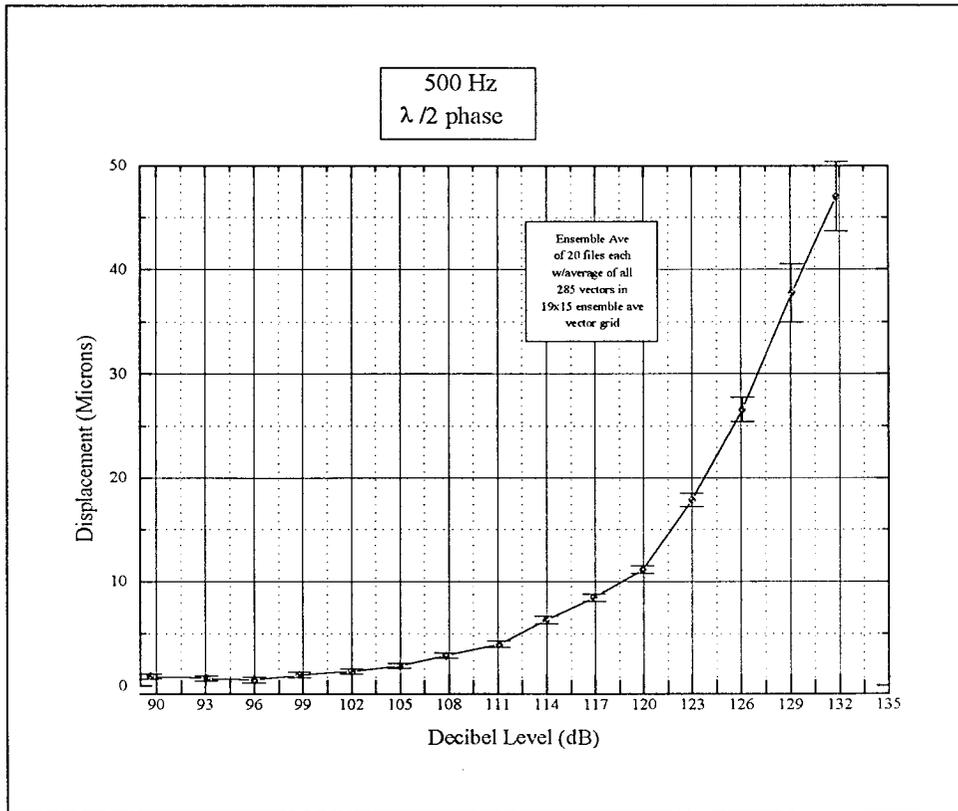


Figure 3. Variation of Acoustic Displacement with increased Decibel Levels at 500 Hz.

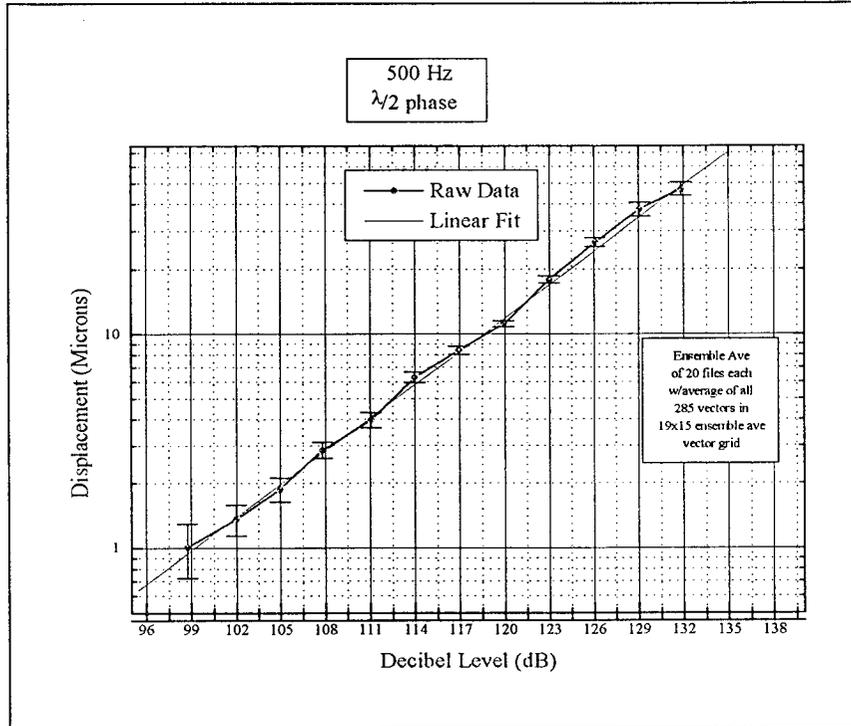


Figure 4. Variation of Acoustic Displacement with Increased Decibel Level (Log10 Scale).

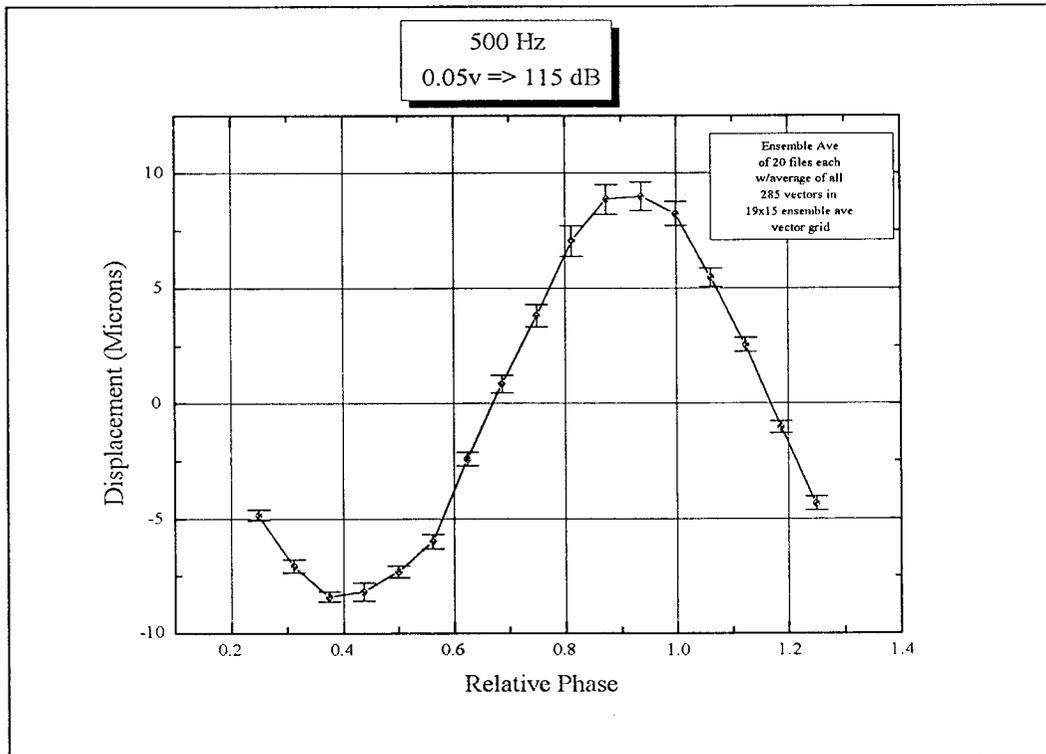


Figure 5. Variation of Acoustic Displacement with Driver/Laser Pulsing Synchronization Phase.

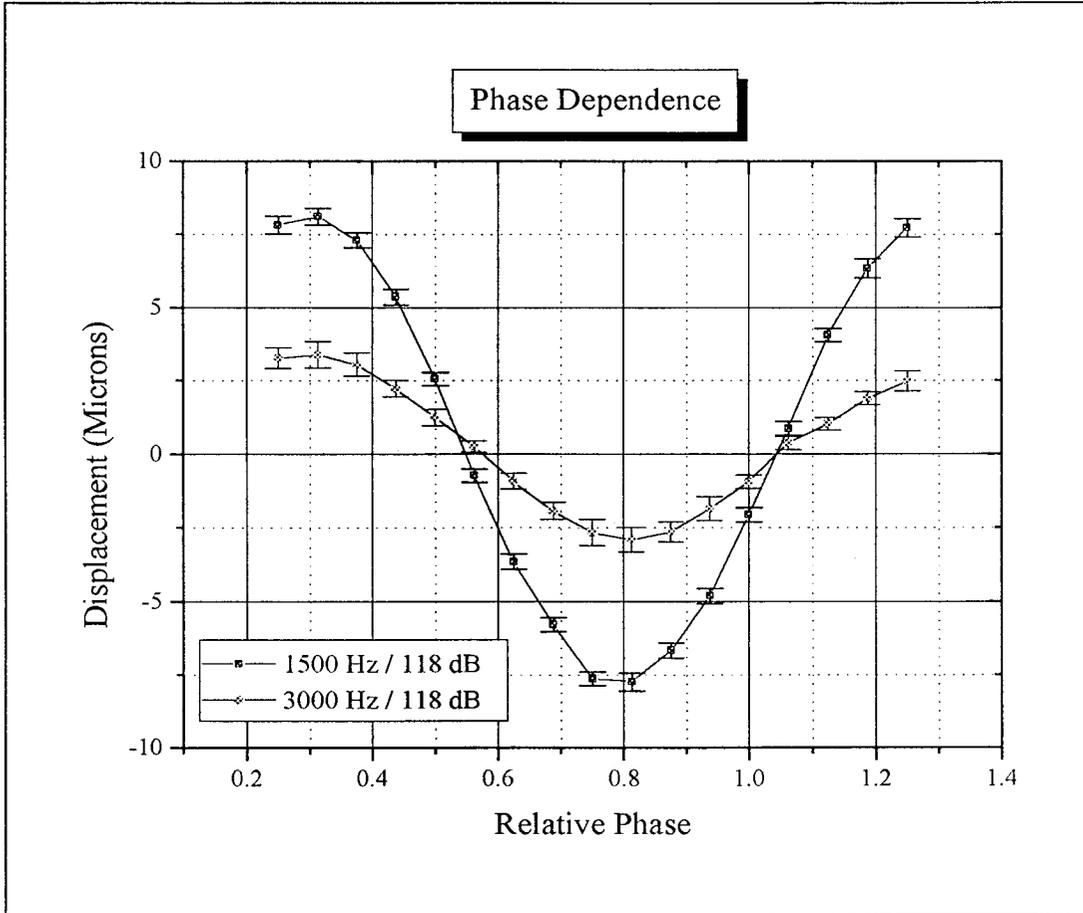


Figure 6. Variation of Acoustic Displacement with Driver/Laser Pulsing Synchronization Phase for 1500 Hz and 3000 Hz at 118 dB.

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