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Apparent nonlinear effect of the microscope on the laser Doppler vibrometer

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National Nuclear Security Administration

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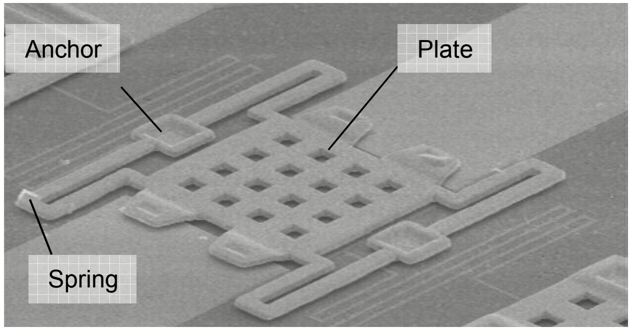
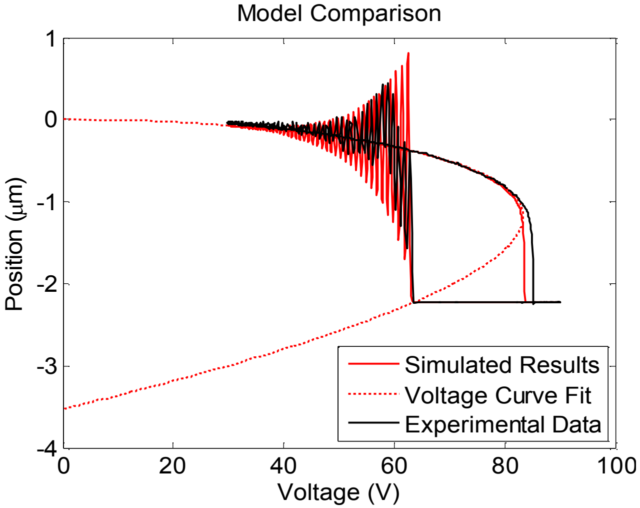
The use of LDV on micro-scale structures is fairly new.

Sandia has used LDV to analyze Radio-frequency MEMS switches.

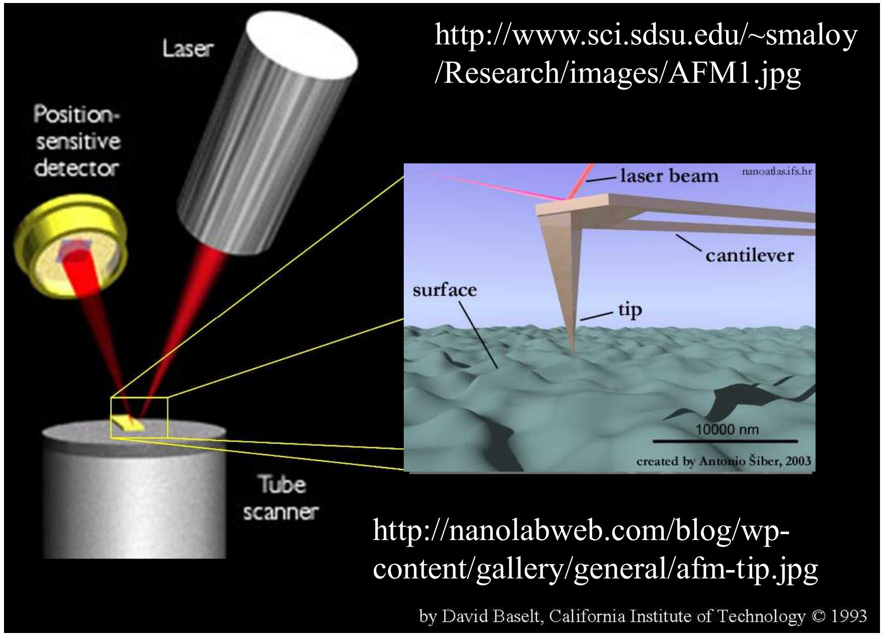




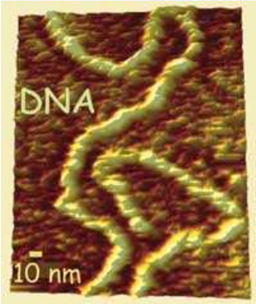
Radio-Frequency MEMS switch, closed by electrostatic actuation: Left: SEM image, Right: Nonlinear displacement vs. voltage, identified from dynamic test.

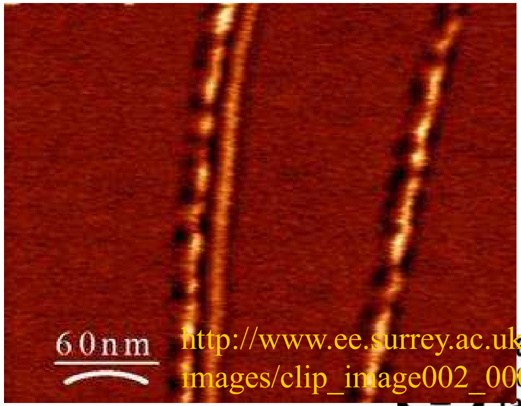
J.Blecke, J.S.Berg, H. Sumali, and D.S.Epp,2006, "RF MEMS Switch System Identification for Control", *Proc. Int. Modal Analysis Conf.*

LDV has been used for analyzing atomic force microscope (AFM) cantilevers.



AFM can image DNA molecules.

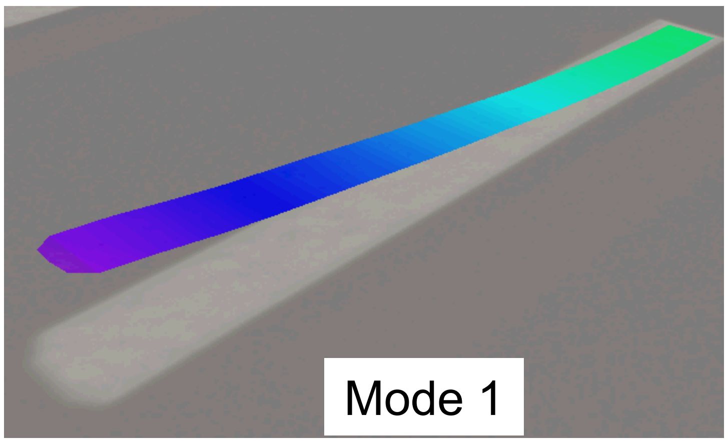


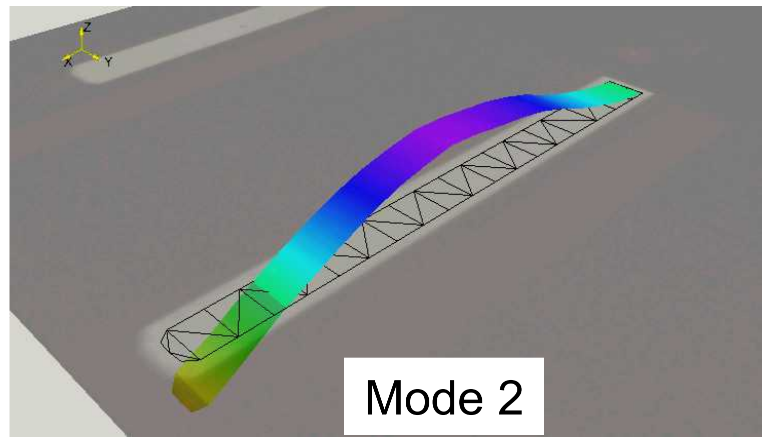


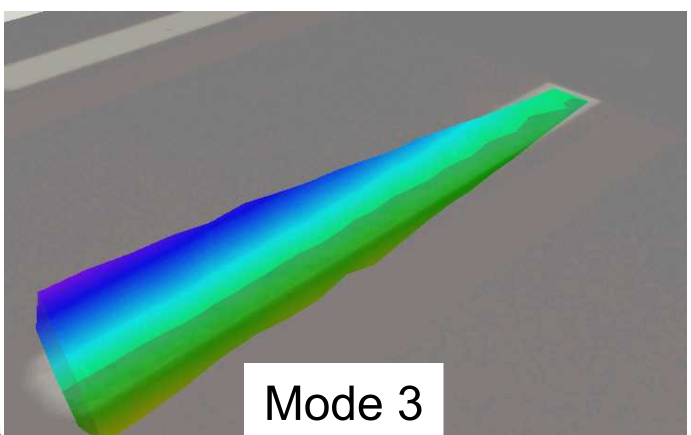
http://www.ee.surrey.ac.uk/NEC/images/clip_image002_008.jpg

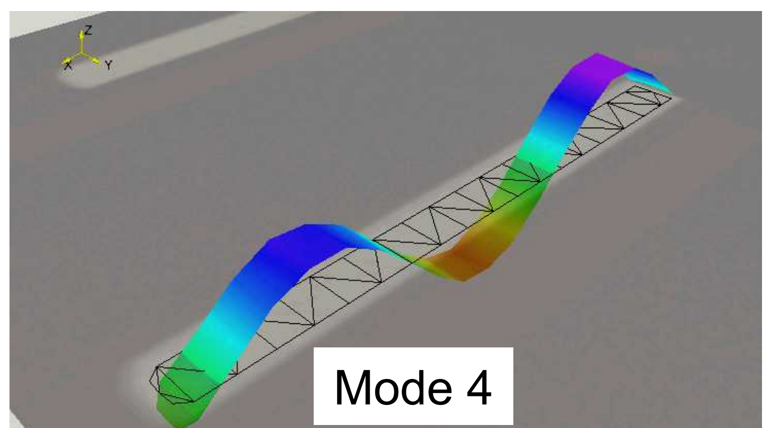
LDV has enabled experimental modal analysis of an AFM probe cantilever.

- Length L=350microns, width b=35microns, thickness h=1micron.
- Silicon density ρ=2300kg/m^3, Young's E=160GPa.



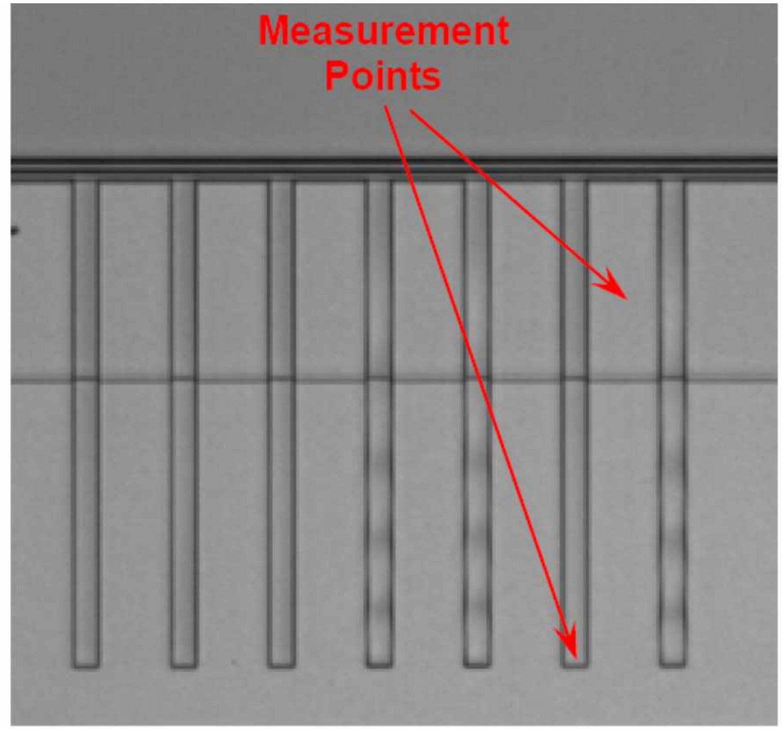


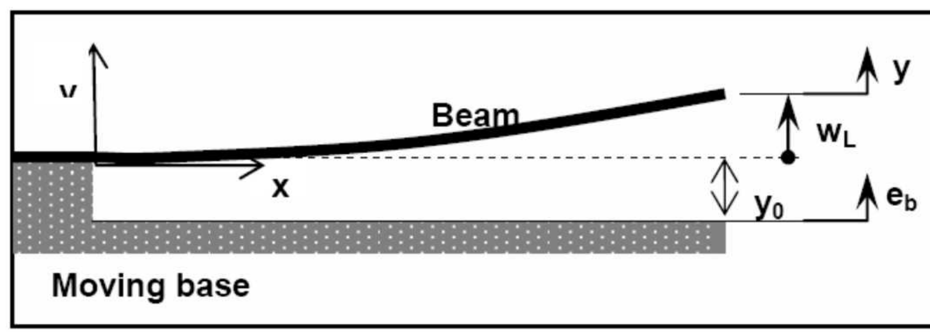




LDV was used for investigating nonlinear behavior of other micro-cantilever beams.

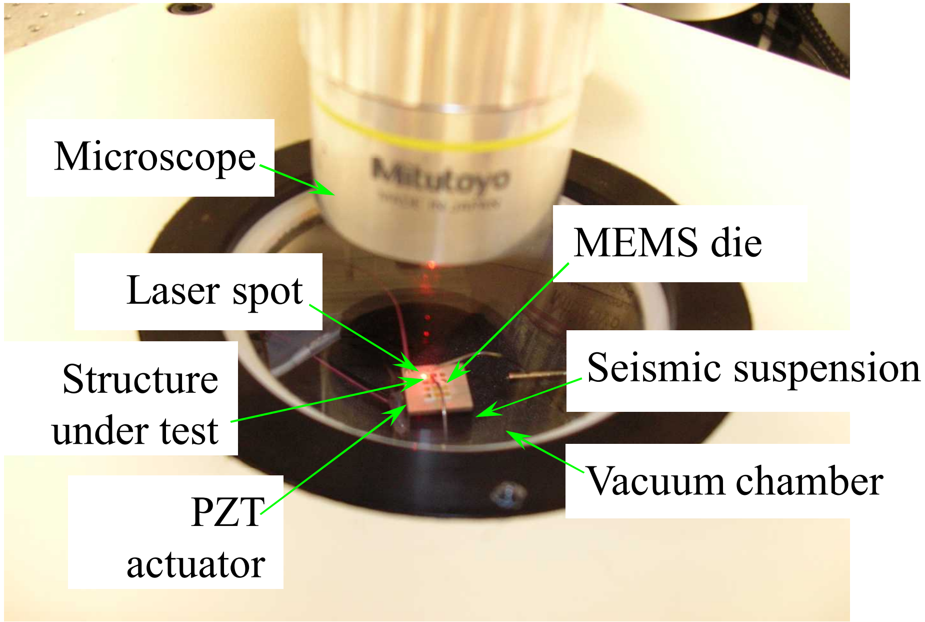
- Micro-cantilever beams manufactured at Sandia using the SUMMiT™ process have been found to respond nonlinearly to base excitation, even at low amplitudes (tip motion = 1/200th of the beam length.)
- A 200 μm by 10 μm by 2.5 μm beam was tested in near vacuum.
- Beam tip and base motion were recorded using a Polytec LDV focused through a Mitutoyo optical microscope.
- Restoring Force Surface method was applied in an attempt to determine the cause of the nonlinearity.

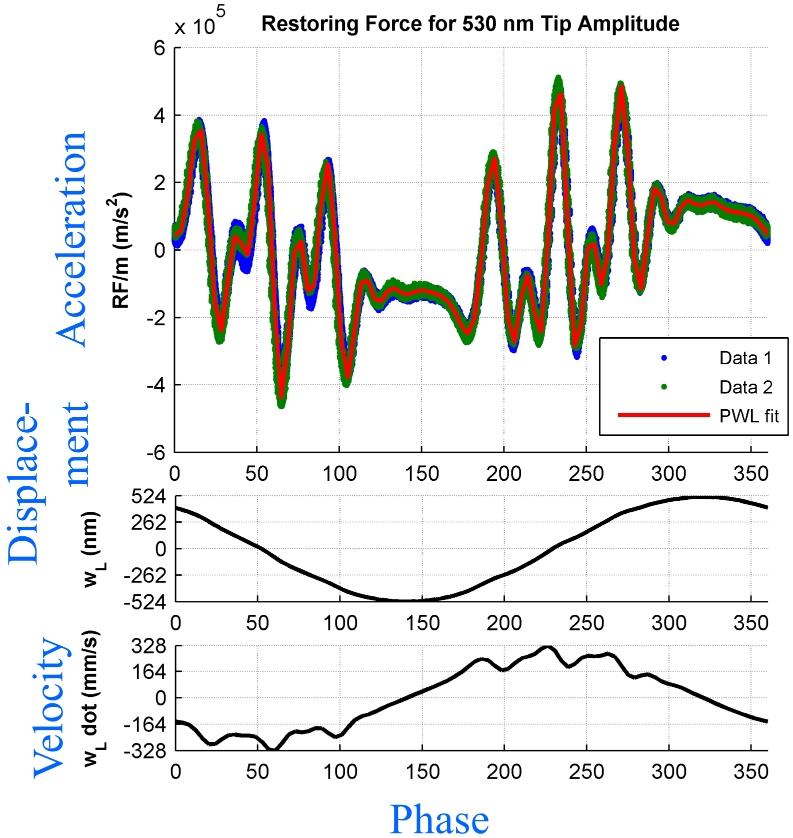




Measurement uses LDV and vacuum chamber.

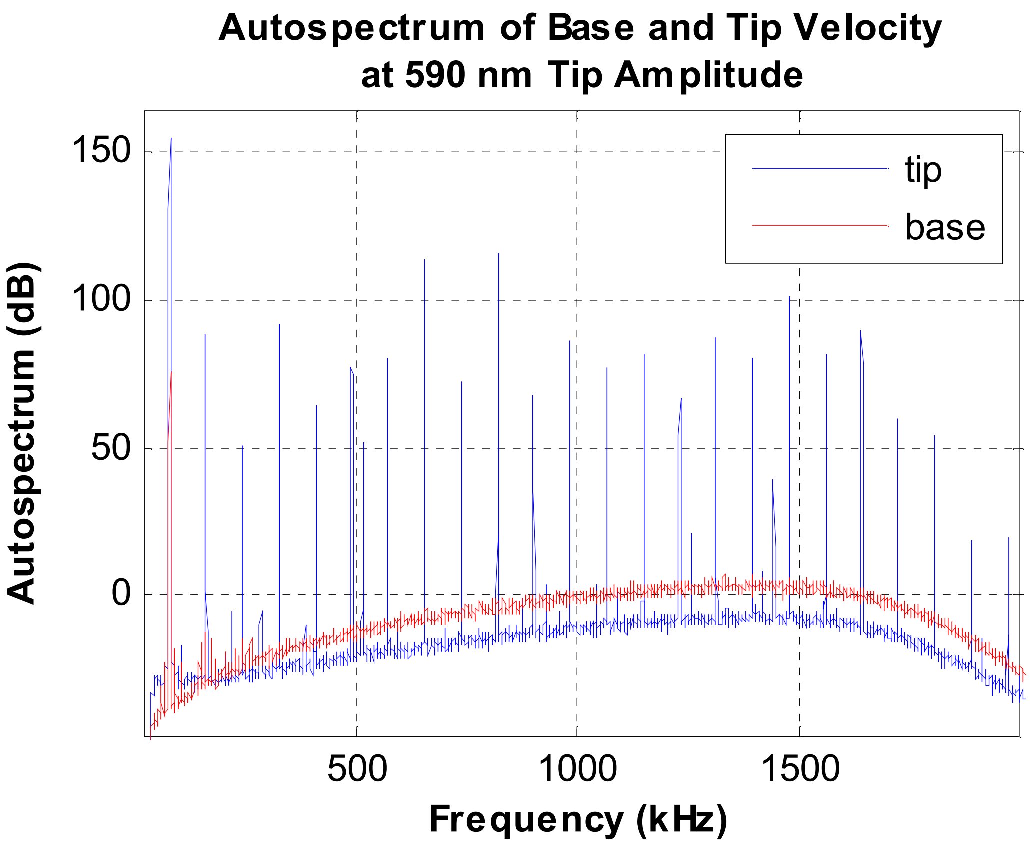
The motion of a MEMS cantilever, forced to vibrate at 82 kHz, was measured with an LDV, focused through a 20X objective lens.





- Substrate (base) was shaken with piezoelectric actuator.
- Scanning Laser Doppler Vibrometer (LDV) measures velocities at base and at 42 points on cantilever under test.

Single-frequency excitation resulted in response with many high harmonics.



- Figure shows beam tip and base autospectra at 530nm tip amplitude.
- Beam tip responds at many harmonics of the excitation frequency.
- No harmonics are visible in base motion.
- The harmonics continue out beyond the 1500 kHz cutoff frequency of the LDV anti-aliasing filter.

Restoring Force Surface (RFS) method was applied to the test data.

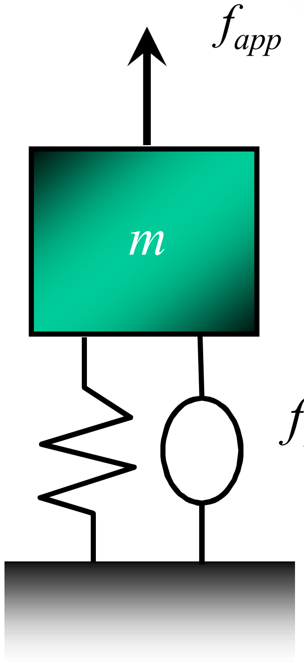
- The RFS method is based on Newton's second law:

$$f = f_{app} - f_{rest}(x, \dot{x}) = m\ddot{x}$$

- For a linear system the restoring forces are:

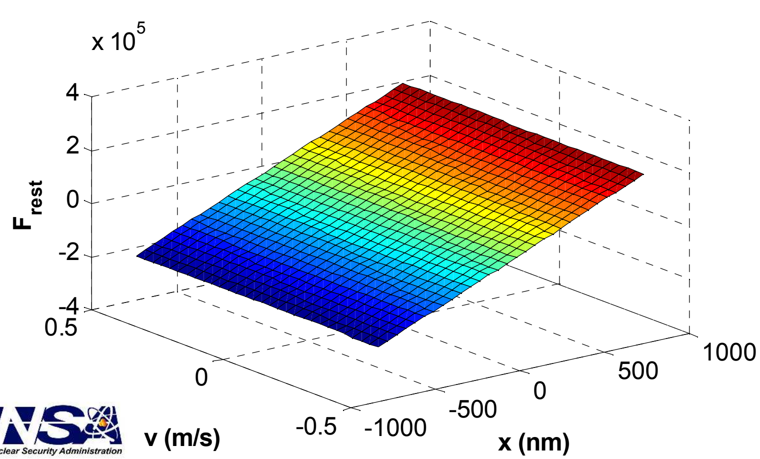
$$f_{rest}(x, \dot{x}) = f_{app} - m\ddot{x}$$

$$f_{rest}(x, \dot{x}) = kx + c\dot{x}$$

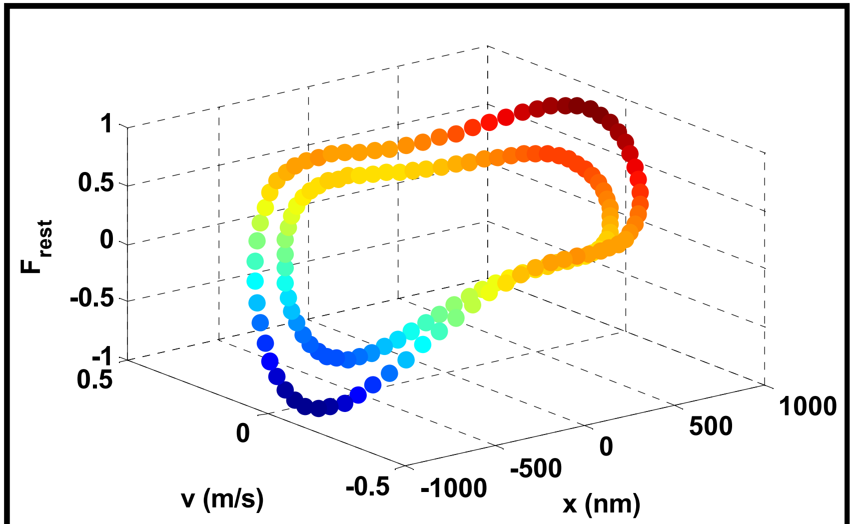


Restoring force surfaces:

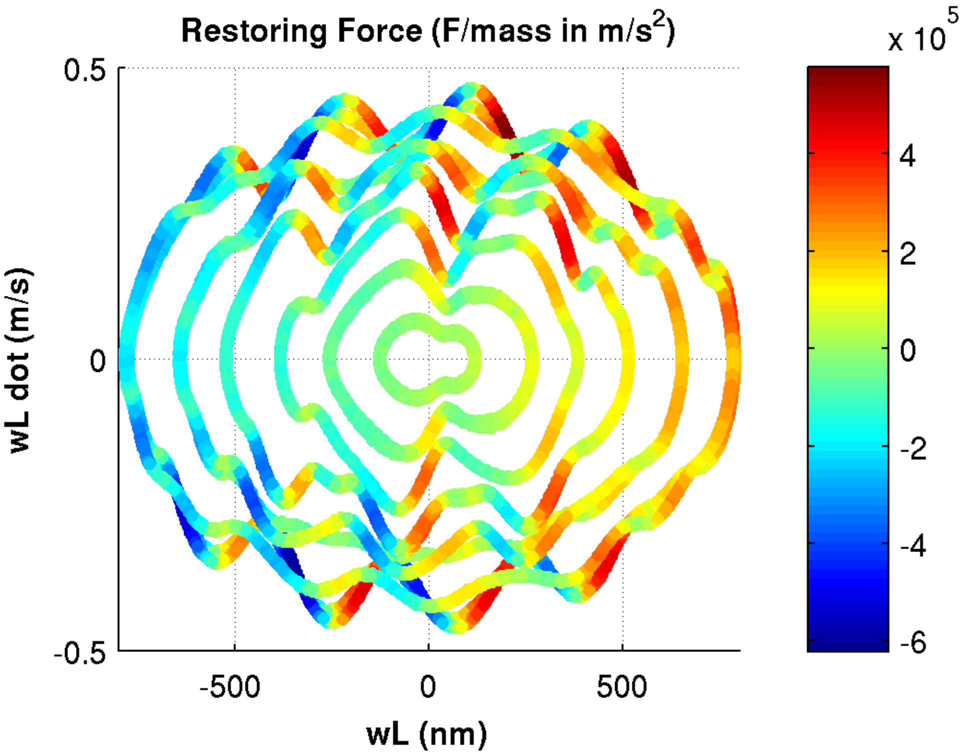
Linear system:



Nonlinear system:



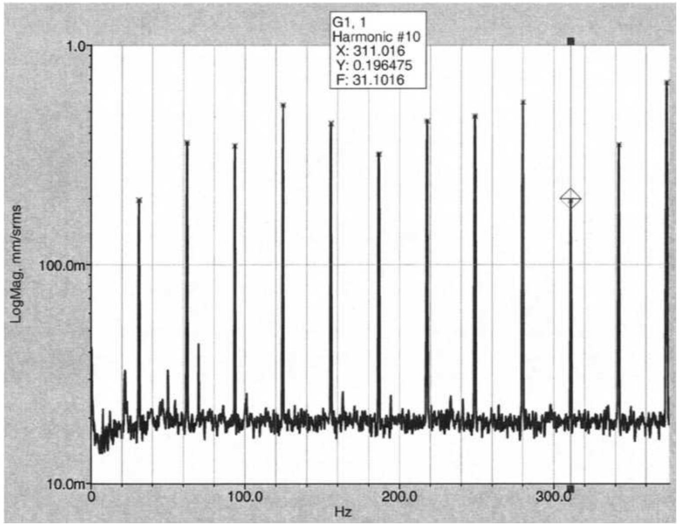
Restoring force surface from LDV measurement was very complicated.



- Measured Force (acceleration) data plotted versus tip displacement and velocity.
- The force versus displacement data shows a linear trend, but there are significant deviations from a linear surface.
- These deviations from linearity occur only at high velocities.
- The representation in this figure is cumbersome (millions of data points) and cannot be used to predict the response of the system.

Nonlinearity may be an artifact of the microscope.

- To make sure that the nonlinearity was not an artifact of the LDV, we tested the LDV-microscope system with a vibrating macro-scale accelerometer.
- Both the LDV and the accelerometer were measuring a sinusoidal velocity generated by an electromechanical shaker.
- Signal from the LDV with the microscope exhibits a nonlinear relationship with the accelerometer signal.

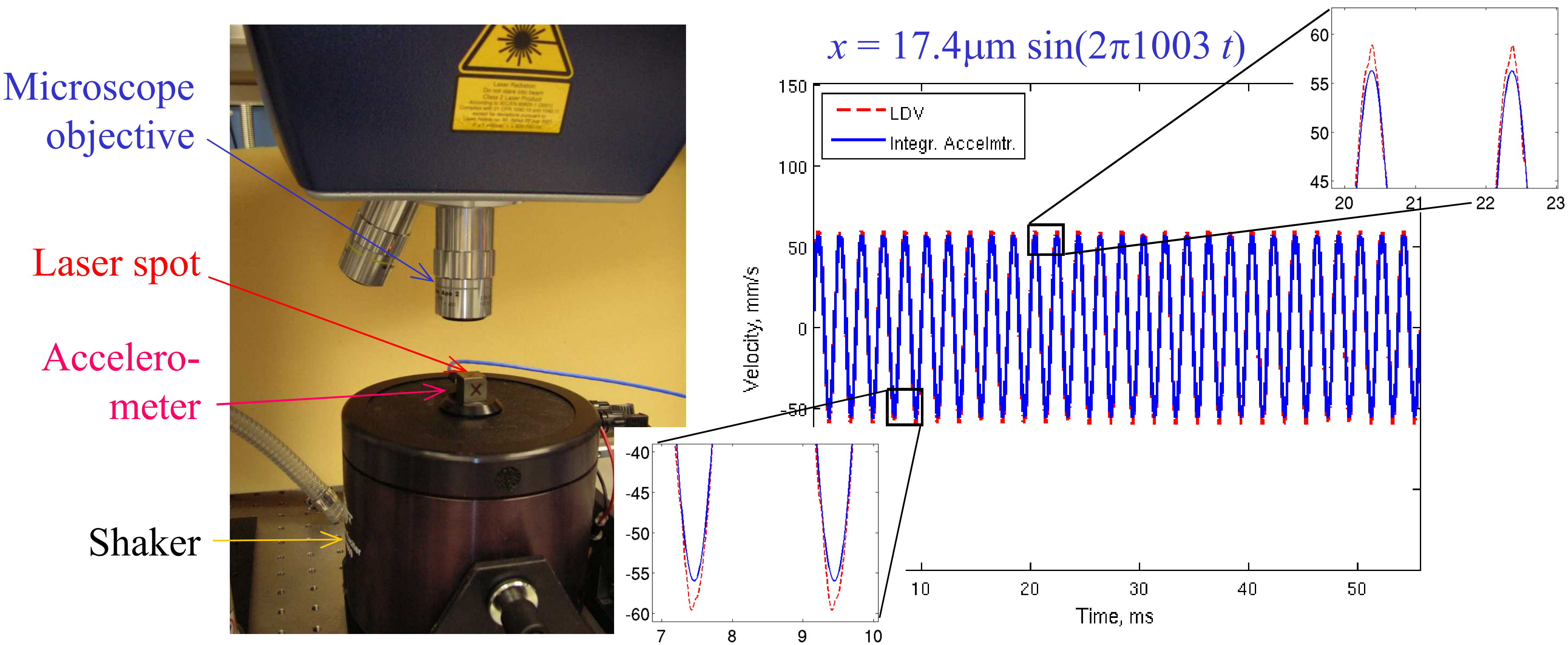


- In-plane motion has been known to cause speckles to generate signals in the LDV that appear as higher harmonics.

S. Rothberg, "Numerical simulation of speckle noise in laser vibrometry," *Applied Optics,* vol. 45, pp. 4523-33, 2006.

Velocity from LDV measurement compares fairly well with integrated acceleration signal.

- On the micro scale, probably no other non-invasive method measures velocity more accurately than LDV with microscope.
- We examine the accuracy of a microscopic LDV with a macro-scale setup, where an accelerometer is the reference.



- The LDV signal matched the time-integrated accelerometer signal well, except around velocity extremes.

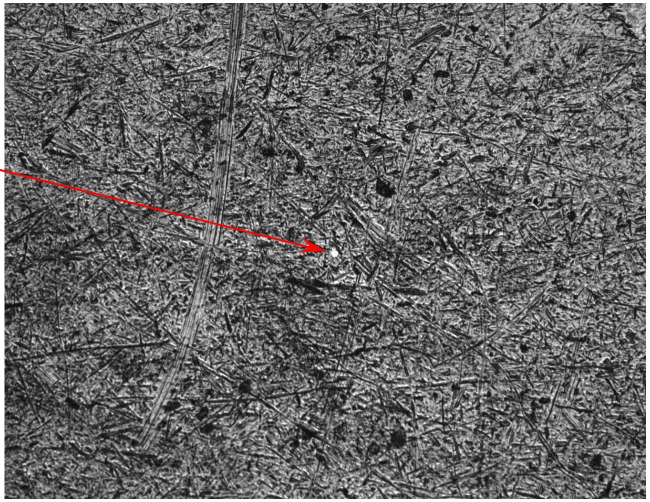
In-plane pseudo vibration does not seem to cause the apparent nonlinearity.

- ‘Speckles’ may have moved in-plane, in and out of the laser spot.

Accelerometer surface under microscope.

Objective magnification 5X

Optics made laser spot image appear larger than actual.



1.8mm

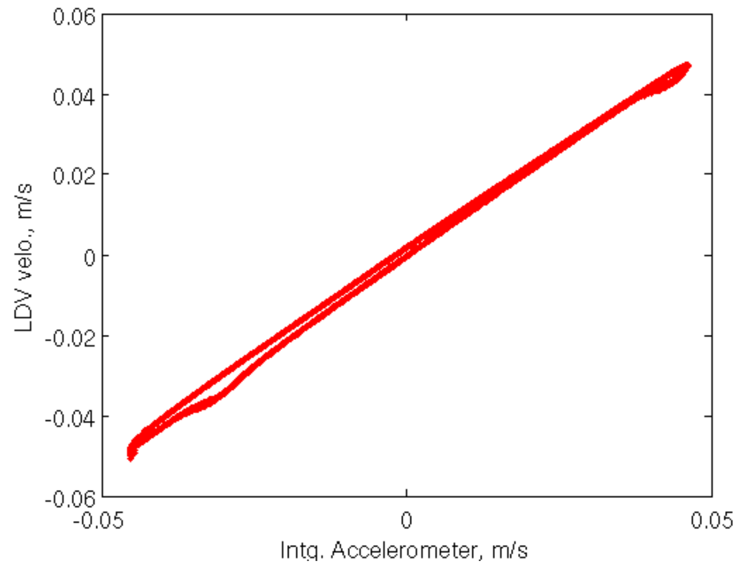
Objective magnification 20X

450µm

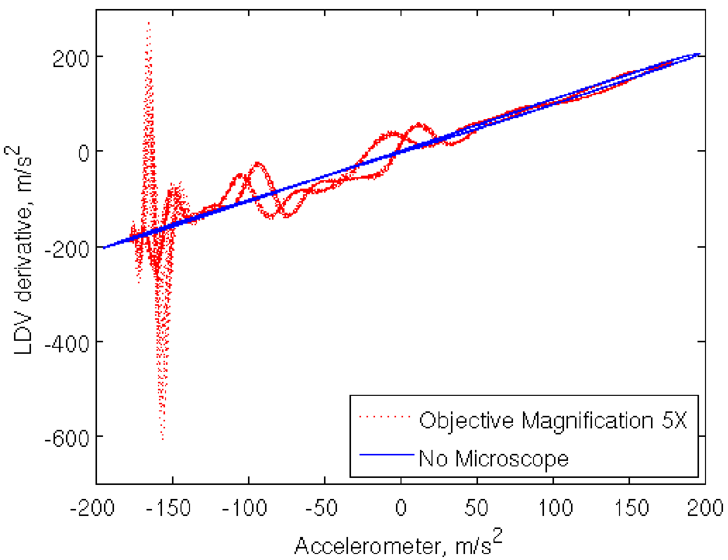
- In the present case, the measured cross-axis motion < -30dB.
- In-plane speckle noise do not explain the nonlinearity.
- Instead, the distortion appeared to be due to the microscope.

Acceleration from LDV appeared to be nonlinear with accelerometer signal.

- For investigating nonlinearities using the restoring-force surface method, acceleration is required.
- Acceleration was obtained by time-differentiation of velocity from LDV.



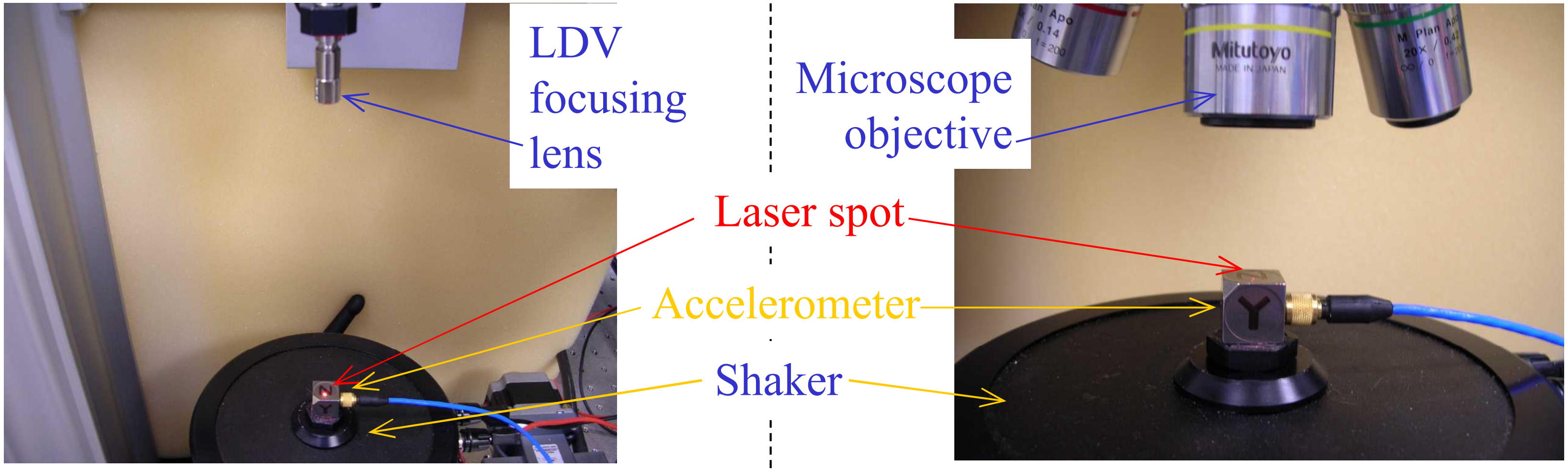
Velocity signal from LDV *with* microscope.



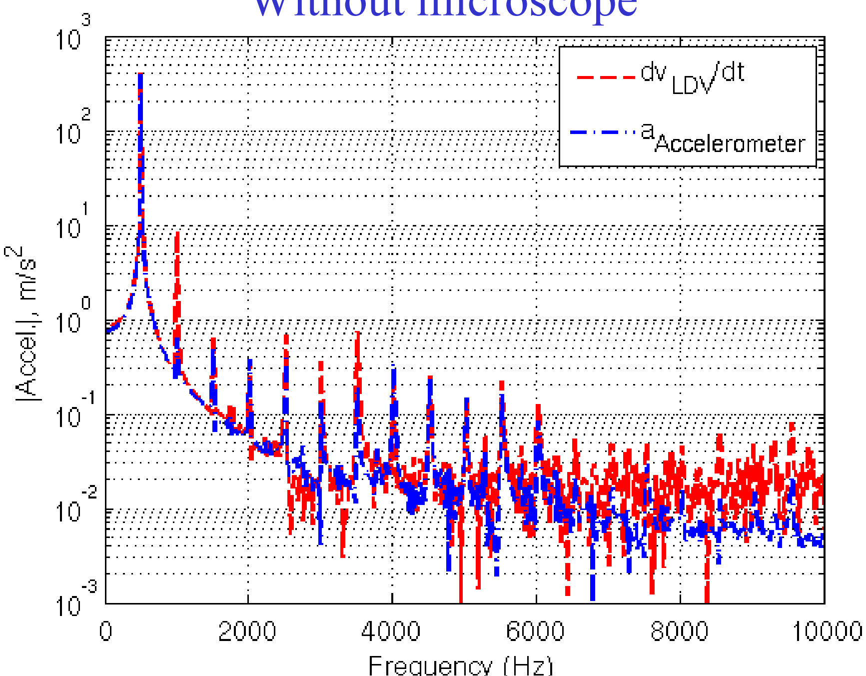
Acceleration from LDV signal with and without microscope.

- Without the microscope, time-derivation of the LDV signal matched the accelerometer signal.
- *With* the microscope, time-derivation resulted in large distortions of the LDV signal.

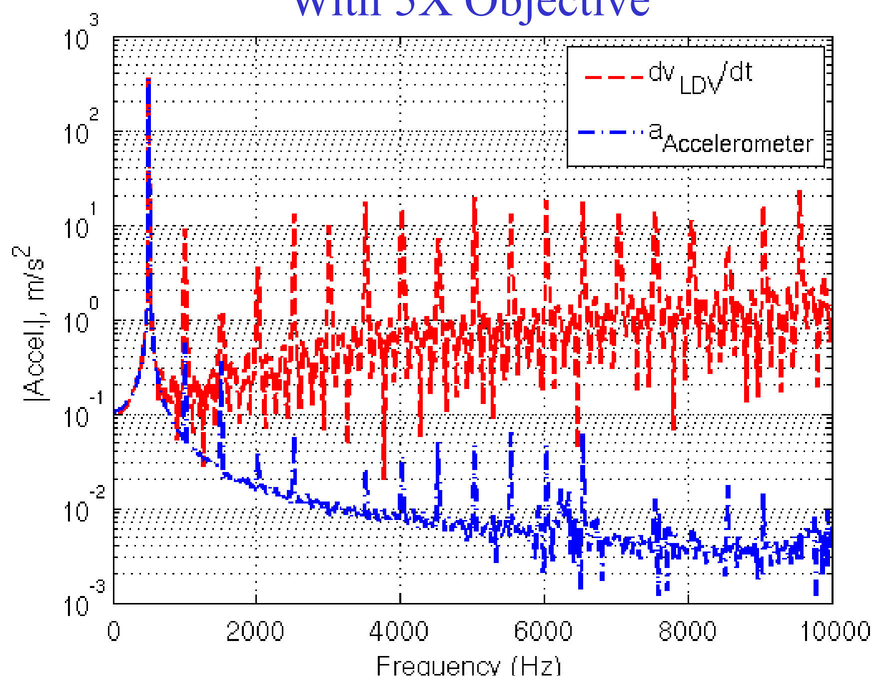
The microscope appears to distort the time-derivative of the LDV signal.



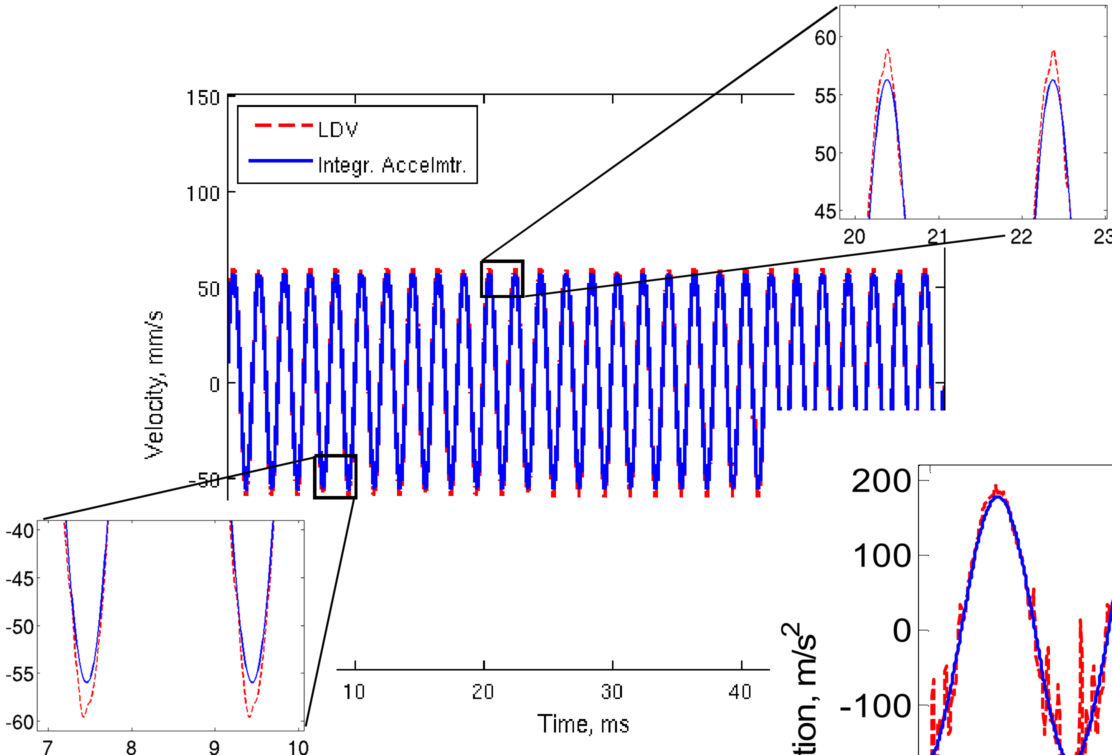
Without microscope



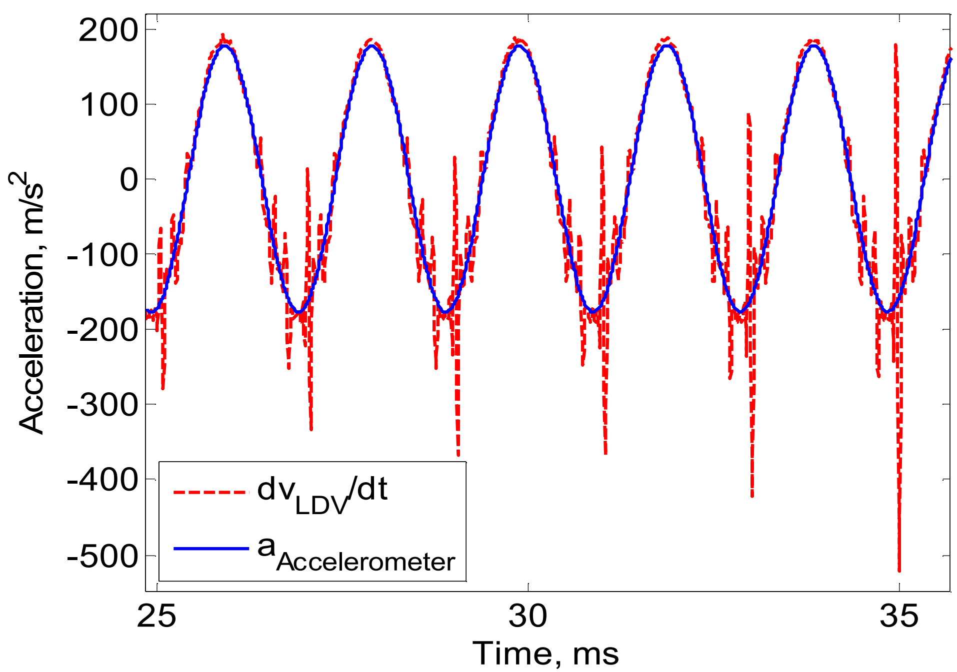
With 5X Objective



Time-derivative of microscopic-LDV signal revealed unexpected drops.



Velocity signal showed little distortion. Did not indicate the source of distortion.

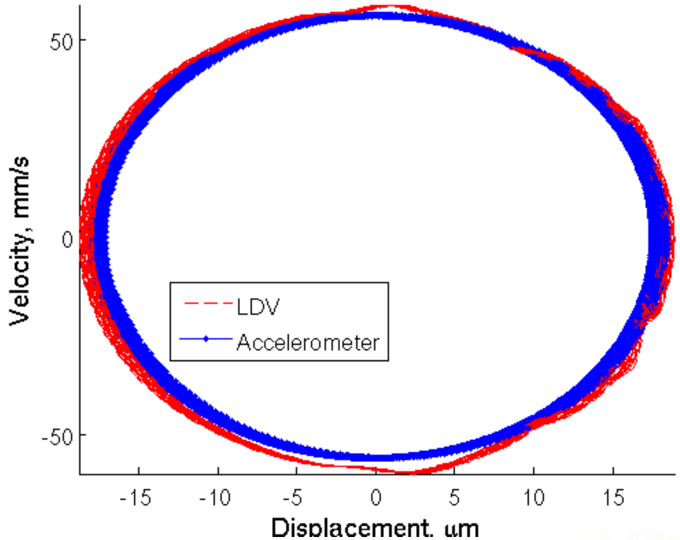


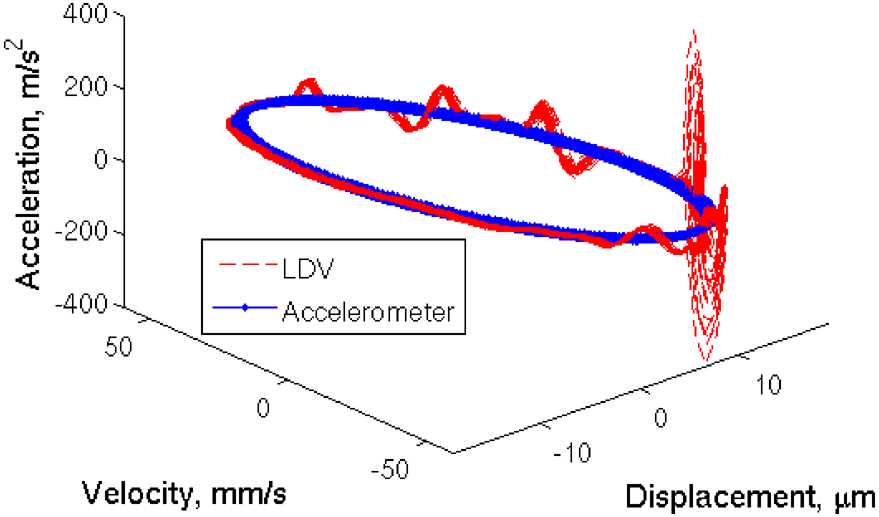
Time-derivation gives much stronger indication to the source of distortion.

✓It is important to examine the ***time derivative*** of LDV signals.

The deflection was larger than the microscope supplier's specified depth of focus.

- The test conditions were all well within the LDV supplier's specifications.
- However, the deflection amplitude was 17.4μm > 14.0μm/2 specified by the microscope supplier.





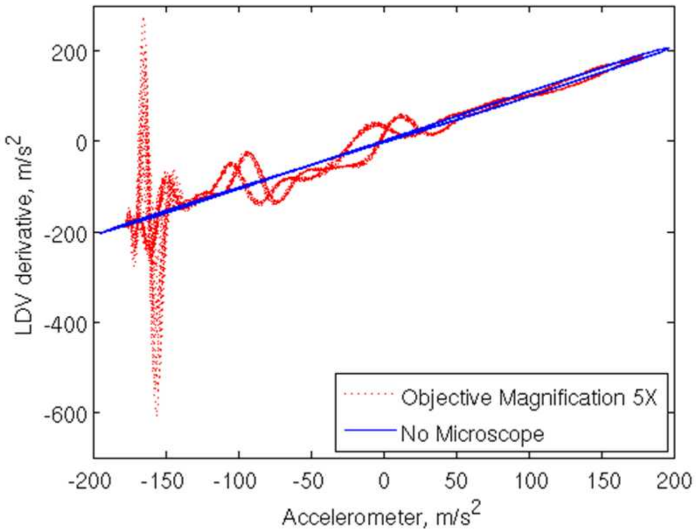
M Plan Apo for Bright Field Observation

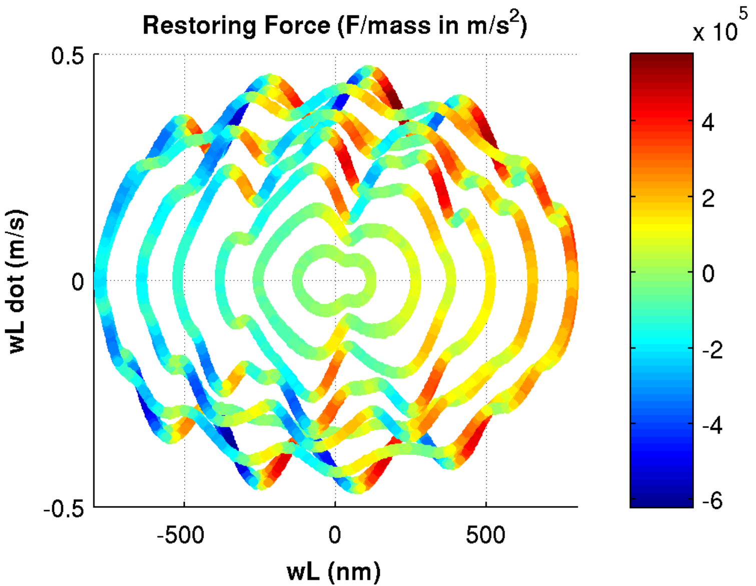
Mitutoyo

Order No.	Mag.	N.A.	W.D.	f	R	D.F.)	View field 1	View field 2	Mass
378-800	1X	0.025	11.0mm	200mm	11.0μm	440μm	ø24mm	4.8x6.4mm	300g
378-801	2X	0.055	34.0mm	100mm	5.0μm	91μm	ø12mm	2.4x3.2mm	220g
378-802-2	5X	0.14	34.0mm	40mm	2.0μm	14.0μm	ø4.8mm	0.96x1.28mm	230g
378-803-2	10X	0.28	33.5mm	20mm	1.0μm	3.5μm	ø2.4mm	0.48x0.64mm	230g
378-804-2	20X	0.42	20.0mm	10mm	0.7μm	1.6μm	ø1.2mm	0.24x0.32mm	270g
378-805-2	50X	0.55	13.0mm	4mm	0.5μm	0.9μm	ø0.48mm	0.10x0.13mm	290g
378-806-3	100X	0.70	6.0mm	2mm	0.4μm	0.6μm	ø0.24mm	0.05x0.06mm	320g

Conclusions

- With or without a microscope, the LDV gives a velocity signal that compares well with time-integrated accelerometer signal.
- Minor velocity distortion from the microscope can result in major acceleration distortion.
- In the test case with the accelerometer, the most severe distortion occurs at high displacement rather than high velocity.
- The LDV with the microscope gives accurate accelerations if
  - the experimental conditions are within specifications.
  - the displacement is within the depth of focus.





- In the micro-cantilever test, the high harmonics were strong even when the displacements < depth of focus (1.6μm for mag. 20X). Therefore, the nonlinear response was not likely to be an artifact of the microscope in the LDV system.

Acknowledgment

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Thank you!

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