Vector Touch Sensor Probe

Shane Woody and Stuart Smith
University of North Carolina at Charlotte, Precision Engineering, Charlotte NC

Introduction

Current contact sensors produce a single pulse or proportionate signal upon being contacted against a surface. The objective of the current sensor development is to determine the vector normal when the spherical tip of the probe is contacted with a solid surface. It is envisaged that this will be used in co-ordinate measuring machines and other applications requiring contact based information. A Vector Touch Sensor (VTS) has two unique features. Firstly, present touch trigger probes produce a single co-ordinate set per measurement and, therefore, require two points of contact to obtain an estimate of local slope. In contrast the VTS probe obtains position and slope from a single measurement thereby potentially doubling the Nyquist frequency. Subsequently, for scanning applications, there will be a potential doubling of the sampling speed for a given accuracy of profile reconstruction. Secondly, current touch trigger probes are limited in size. Consequently, metrological applications such as diesel injectors, MEMS and fiber optic technologies may be impractical. Contrary to market designs, VTS probes are not limited by geometrical scaling and thereby, may be adapted for the measurement of work-pieces with significantly smaller dimensions. The current sensor is fabricated with phase lock loop signal conditioning and piezo-electric ceramic (PZT) sensor/actuator pairs. This abstract presents a theoretical ideal for performance evaluation, a method for probe signal analysis, results from the characterization of three successive probe designs and shows a fourth generation probe.

Principal of operation/definitions

The principal of operation for VTS probes is based on the characteristic properties of both resonant frequencies and the associated phase response. Classically, output strains to input energy ratios are substantially higher at harmonic resonance and the phase response will lag by 180 degrees [1]. The rate of phase change with input frequency is determined by energy dissipation mechanisms. In general, the VTS resonating system is composed of a rigid rectangular metal bar with a ruby sphere attached to one end. Several pairs of piezo-electric elements (PZTs) are bonded on each side of the metallic bar. Functionally, PZTs will expand and contract when energized by an AC signal and vice versa. Hence, several PZTs function as actuators to the probe and additional PZTs detect the strains as they propagate through the rectangular body [2].

Consider a single lateral vibration about the axis of the metal bar while a constant force is applied about the VTS sphere. The magnitude of phase change will be greatest when the contact is co-linear to the vibrating axis and least along the orthogonal axis. Uniquely, this effect will be independent for each orthogonal, lateral vibration as long as the resonating frequencies are distinct. Thus, it might be expected that, at resonance, each lateral axis' phase response for a constant force load about the sphere varies harmonically with angle of contact, θ, figure 1. Additionally, phase response for the resonating longitundinal axis (z-axis) will also vary harmonically with angle β as shown in figure 2. In this case, phase response is greatest when the applied force is contacted on top of the sphere or directly in line of the *z*-axis. Theoretically, phase response for the two lateral axes and single longitudinal axis will provide the necessary components to construct a three-dimensional phase sensitivity plot for any location about the probe's sphere, figure 2. Conceptually, each resonating axis can be characterized by two complete spheres based on the phase response at any location on the probe head due to a constant applied force load. Thus, the entire 3-D plot for all three resonating axes can be mapped by 6 nested spheres.

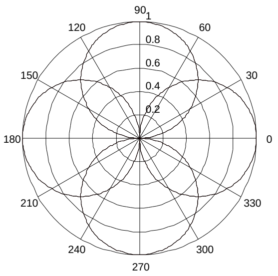

Figure 1: phase response plot for two orthogonal vibrations at constant applied force

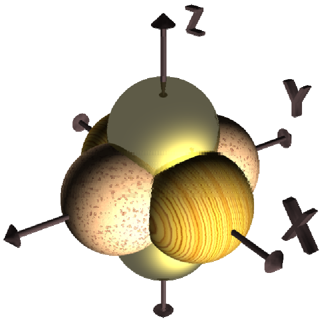

Figure 2: theoretical 3-d phase response for three resonating axes at constant applied force

Careful consideration is taken to precisely detect the output response due to added stiffness or damping upon contact with the probe head. In practice, two modes of measurement are possible. Firstly, mode I detection consists of exciting the probe at a harmonic frequency and tracking the magnitude of phase shift as contact force is added. Mode II utilizes phase locked loop (PLL) techniques and thereby, locks into a desired phase and measures the magnitude of frequency shift due to the added contact force [3].

Contact forces are measured using a simple notch flexure and capacitance gage, calibrated using dead weights with a resolution of 0.2 mN over a 300 mN range. The flexure is mounted to a single translation stage with a resolution of 1 nm and maximum displacement of 15 μm and the entire assembly is brought into contact with the probe sphere, figure 3. To provide contact forces at known locations on the probe sphere, the VTS probes are mounted to two stacked horizontal and vertical rotary tables. This provides two rotational degree of freedoms for the probe head. Also, LabView ä is used to communicate through a DAQ card to control the force while simultaneously detecting phase response for each resonating axis, figure 4.

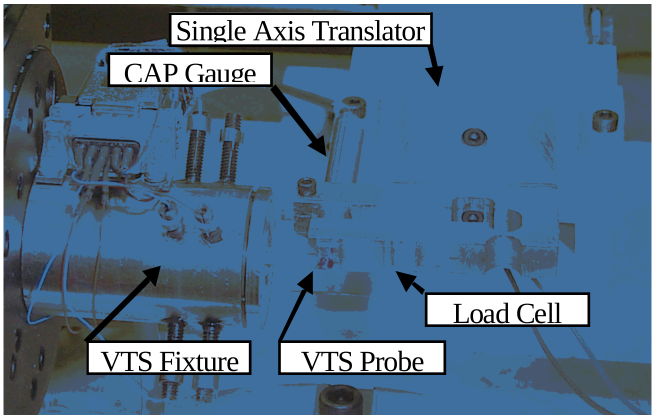

Figure 3: Experimental Apparatus

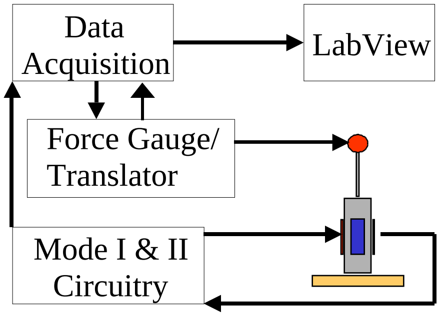

Figure 4: Experimental Procedure

Independently, each resonating axis provides a phase shift from which all three in combination may be analyzed to determine direction of applied force about the sphere. Each constructed phase response plot corresponding to figures 1 or 2 is only valid for a constant force. Therefore, a triggering force algorithm is needed evaluating the direction of applied force. Assuming the phase response for each axis varies harmonically with angle of contact as represented by figures 1 and 2, suitably scaled, the three phase responses may be combined to produce the root mean square (RMS) value. This RMS value will be the same at any location about the sphere for a specified applied normal force. In essence, during a scanning process, the three, combined phase responses will dependently provide the required triggering mechanism for instantaneous position of the probe and the direction of applied contact.

Probe development

As described above, triggering force on the entire sphere by way of RMS is only possible if all 6 spheres in figure 2 are of the same size. If this is not the case, scaling each phase response axis with respect to one another is a possible solution. However, this only applies if the two sensitivity spheres for each axis are the same. In an effort to achieve this, it has been necessary to undertake four generations of VTS probe design, see figure 5. Generations 1 and 2 have revealed that a pair of PZT actuator and sensors placed on opposite sides produce asymmetry in a single axis. Basically, the phase response, as in figure 1, is greater when a constant force is contacted on the sensor side and phase response slightly diminishes in comparison when contacted directly in line on the opposite, actuator side. Generations 3 and 4 address this by symmetrically placing PZT actuator/sensor pairs.

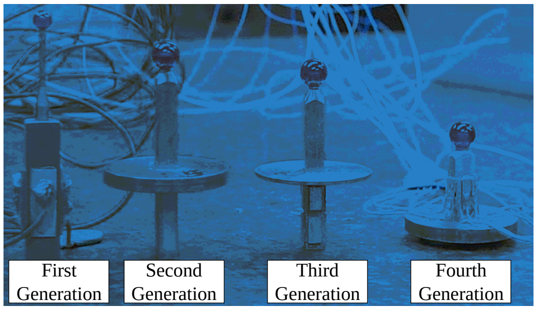

Figure 5: VTS generations

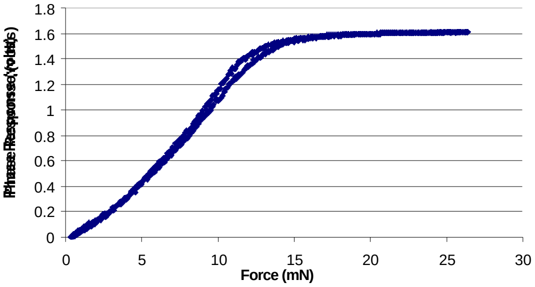

Figure 6: phase response for a longitudinal frequency Vs force load (contact point located at the top of the sphere or normal to the z-axis)

Additionally, generation 1 probes were threaded at the end of the bar and excited at first harmonic [3]. Experimentally, it was determined that threading caused non-repeatable phase response and resulted in a low Q value. Thus, a second-generation probe was designed with mountings located at node locations along the bar. This generated higher Q values but the phase response in each axis was not symmetrical. Thus, two non-systemically circular patterns were produced in each axis, see figure 7. The third generation attempted to combat the symmetry of phase response by bonding PZT sensors on all sides of the beam. In addition, actuators were also placed on each side in order to amplify the input energy. A total of 4 sensors and 4 actuators were placed around the third generation VTS probe (i.e. a sensor and actuator on each side of the beam). A comparison between the phase response of the second and third generation probe 2 is presented in figures 7 and 8. From these figures it can be seen that the third generation partially improves the symmetry problem.

As discussed previously, mode I and II refer to locking into frequency and tracking phase response and locking into phase and tracking frequency respectively. Current probes may produce a linear phase response for loads of 1-10mN. However, at higher loads this tends to exhibit ‘saturation’, see figure 6. This is due to the sharpness of the phase change about the resonance. In practice, as stiffness is continuously added to the vibrating system the resonant frequency will increase with the monitored phase following the characteristic curve for a second order system. When the resonant frequency has shifted to a value far from the ‘free’ resonance, the phase shift will tend towards a constant. The advantage to phase locking circuitry, mode II, the change in natural frequency may be continuously measured over an arbitrarily wide load-range.

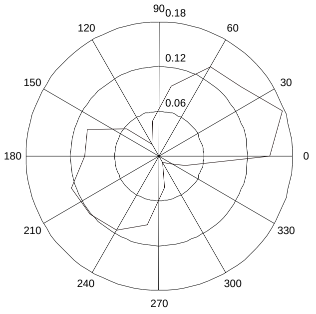

Figure 7: second generation phase response plot of a single axis

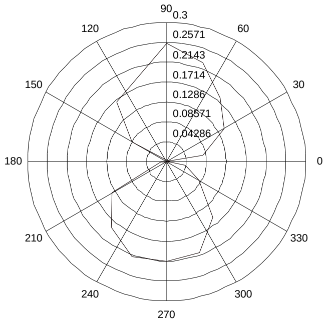

Figure 8: third generation phase response plot of a single axis

Current research aims to improve the phase response for a lighter force load while improving the symmetry of the phase response. Generation four is currently being assessed. As shown in figure 5, the generation four has an air gap separating the probe head and rigid base. The ceramics bridge the gap between the rigid base and the probe head. Initial results indicate a high sensitivity to contact force.

References

[1] Rayleigh, J.W.S., 1894, *The Theory of Sound*, Dover Publications, Inc. (1945).

[2] Vidic M., Harb S.M. and Smith S.T., 1998, Observations of contact measurements using a resonance based touch sensor, *Precision Engineering*, **22**(1), 19-36

[3] S.C. Woody and S.T. Smith, Vector Touch Sensor Probe, *Proc. of ASPE*, 1998, **18**, 471-474