All Format Surfacing

Innovation is typically classified in two distinct categories. The first and most common has been termed "Incremental Innovation" while the second, called "Radical Innovation[1]" is much less frequent, however significantly more far reaching in its implications. According to Richard Luecke[2], incremental innovation either *"improves upon something that already exists, or reconfigures an existing technology for a new purpose"*, whereas he states "*…radical innovation, in contrast, is something new to the world, and a departure from existing technology or methods".* When radical innovation occurs it often has dramatic and far reaching effects within its field of application.

A good example of incremental innovation can be seen in the continual improvements experienced in generating technology that have allowed migration from the old style toric "cup wheel" generator to the more modern and accurate CNC technologies we see today. We can reminisce back 15 years ago to the Gerber "SGX" and Coburn "IQ" generators, evolving forward to the LOH V series machines (V50, V75, V95, VPro, etc.). These *incremental* improvements in generating technology allowed surfacing to evolve from two step smoothing (fining) to one step, then onwards to "cut to polish", completely eliminating the smoothing step.

The Leap to Freeform:

It is generally agreed that the implication of freeform surfacing is such that it will allow a shift away from the traditional moulding of PALs (Progressive Addition Lenses), towards direct surfacing of complex curve geometries. For this reason it is expected that the industry will change deeply and significantly, affecting all levels of the manufacturing / distribution chain; thereby characterizing freeform technology as *"radical"* innovation. This new technology does not only enable the manufacturing of lenses with a free form surface (i.e. a surface defined point by point) but also of spherical and toric surfaces. We therefore should call it All Format Surfacing.

It can be argued that the improvements to generating and polishing technologies have been incremental in nature; however the jump from hard lap based processing to the soft / flexible based polishing necessary for true freeform processing has proven to be a high hurdle, and as such is a much bigger step than a simple incremental improvement of existing technology. The leap to ***all format surfacing*** (combination of freeform generating with flexible polishing) requires not only micron level form accuracies, but nanometer level accuracies at the "mid spatial" surface frequencies.

In the past few years the optical industry has been introduced to new generators having the "promise" of freeform, however lacking in either accuracy, productivity, and/or robustness; thereby making them unsuitable for practical or economical freeform production. Many customers have purchased these generators in order to experiment with freeform surfacing; however the great majority have been disappointed and have come to realize that the difficulties experienced were too great to permit successful implementation of a controlled process. As a result, these "freeform" machines are being generally used for more conventional toric *"cut to polish"* work, this however at high costs per surface. The most recent generating and polishing technologies have however contributed to progress the state of the art to the point where freeform surfacing has become fully realized. Examples of these new technologies can be seen in the new Satisloh *VFT* series of generators, and the *iFlex* series of polishers. These machines are felt to be an important departure from what was previously available. Never has the leap from conventional surfacing to freeform been so easy, and for this reason the industry is now beginning the conversion process

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[1] The terms *"breakthrough innovation"* and *"discontinuous innovation"* are often used as synonyms for "*radical innovation*".

[2] Richard Luecke, *"Managing Creativity and Innovation"* (Boston: Harvard Business School Press, 2003), 2 - 5.

of changing their production lines to install true “flexible surfacing” equipment. But what makes these machines work so much better than their predecessors? What is truly important to a successful freeform manufacturing process?

Accuracy, vs. Performance

In a conventional machine tool or generator, brute performance generally equates to how fast you can remove material from the lens or part being machined. The accuracy requirements in these machines are typically 10X lower (allowed errors 10X higher) than in the new freeform class of machine such as the Satisloh VFT. In this new machine class, surface accuracies need to be consistent and compatible with the new follow-on flexible polishing processes, whereas the “hard lap” surfacing of simple torics is quite forgiving since it can fix a multitude of surface errors. As such, when surfacing freeforms, one becomes sensitive to errors in the sub micron, and even in the nanometer regimes. This results in the need for new machines to be capable of both heavy stock removal, ***and*** of having the additional ability of ultra-accurate, high speed position control consistent with the complex geometries of the new “*toro-freeform*” surfaces.

Some people have argued that in order to make a machine accurate, it needs to have a heavy tool slide. They stated that the heavy mass provides inertial resistance to external disturbances (cutting forces). Although this can be true for machines used in slow moving applications like the old style generators; it is totally false when considering the fast moving, high frequency demands of freeform surfaces. LOH has always been a champion in designing heavy / robust slide systems, however what counts here are high bandwidth and high force / acceleration capabilities, not a high mass slide.

The tool slide in a single point diamond turning machine needs to accurately follow the rotational asymmetry of the lens at high speed. To accomplish this, the machine needs to have both high acceleration and high bandwidth capabilities; but what is the difference between the two, and why are these important?

Acceleration: In the simplest case the turning machine would be cutting a sphere (or asphere). Since the part is rotationally symmetrical, only a very slow in-feed coordinated with a slow cross feed motion is required. A toric lens however requires a rapid oscillation of the tool (in-feed axis) at a frequency of 2X the rotational frequency. This motion is generally sinusoidal so acceleration can be represented with the following equations:

$$\mathbf{x = h \sin (wt)}$$

$$\mathbf{a = -h w^2 \sin(wt)}$$

therefore

$$\boxed{\mathbf{a_{max} = h w^2}}$$

Where:
x = position of tool in the X direction
a = acceleration of the tool in the X direction
h = representation of the tool travel (total tool travel = 2h)
w = Two times the rotational velocity of the lens (radians per second)
t = time (seconds)

From this, we can readily see that the peak acceleration ($\mathbf{a_{max}}$) is dependent on the tool travel, and is proportional to the square of the rotational velocity. Since machine productivity is generally proportional to the rotational speed of the lens, we can see the importance of the acceleration capability of the tool. Doubling the rotational velocity will generally reduce cutting time by a factor of 2 but will require four times the acceleration.

From Newton's 2nd law:

a = F/M

where "F" is force of actuator and "M" = moving mass of actuator

To reach high accelerations, one has to keep the force F high and the mass M low. For this reason Satisloh designed the VFT fast tool with a very low moving mass, and a very high force voice coil actuator. This combination allows us to achieve the highest accelerations, and therefore the highest productivity freeform turning process in the industry. Also many will certainly remember Newton's third law which states; "***To every force of action there is an equal and opposite reaction***". When accelerating a heavy tool one will see more reaction force transmitted into the machine base, and potentially into the lens surface than when accelerating a low mass tool.

Bandwidth: Acceleration however only partially addresses machine performance. The concept of bandwidth is one of even greater importance. The tool in a freeform turning system needs to accurately follow the lens curve, even if this curve is a complex PAL design. One can define bandwidth as follows:

> ***Definition:*** *Bandwidth is the maximum frequency at which a system can follow a given (sinusoidal) trajectory without loss of accuracy. (i.e. within a standard error tolerance of no greater than 3dB in amplitude attenuation and / or 45 degrees of phase lag).*

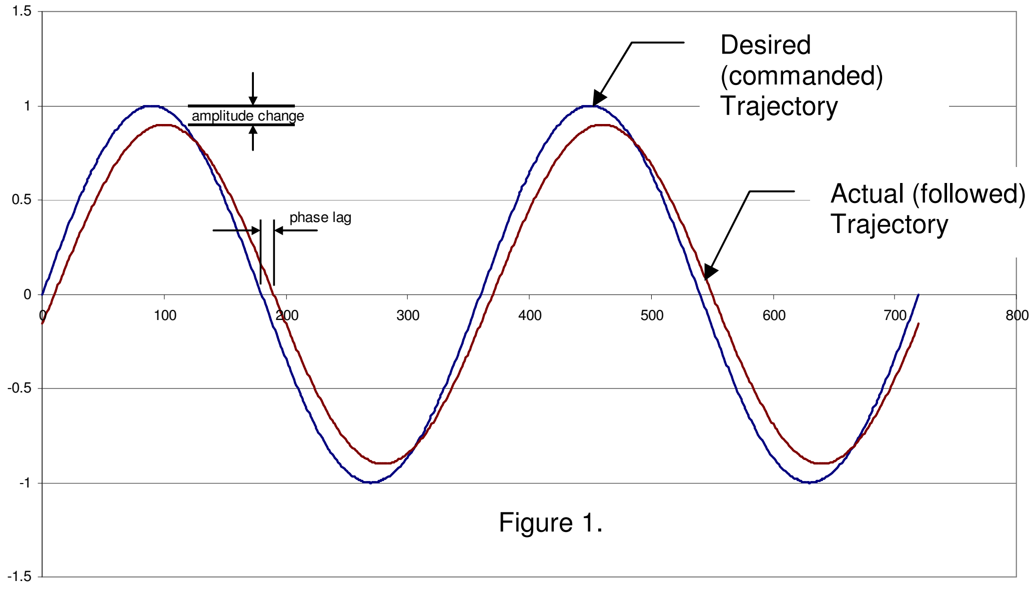

Figure 1.

So why is bandwidth important?

It all comes back to accuracy and performance.

The higher the bandwidth of the system, the higher we can push the rotational velocity of the lens while keeping surface errors within tolerance. A system can have a high acceleration capability, but still be unable to deliver high bandwidth.

Frequency Content: One way of understanding a lens surface is to look at the "frequency content" of the lens. To simplify things further one needs to look at the frequency content of one revolution of the lens at a given radius. For a progressive, or even a toric lens this circular path will have a changing height dependent on the angular position of the tool relative to the lens. This can be seen in Figure 2 below.

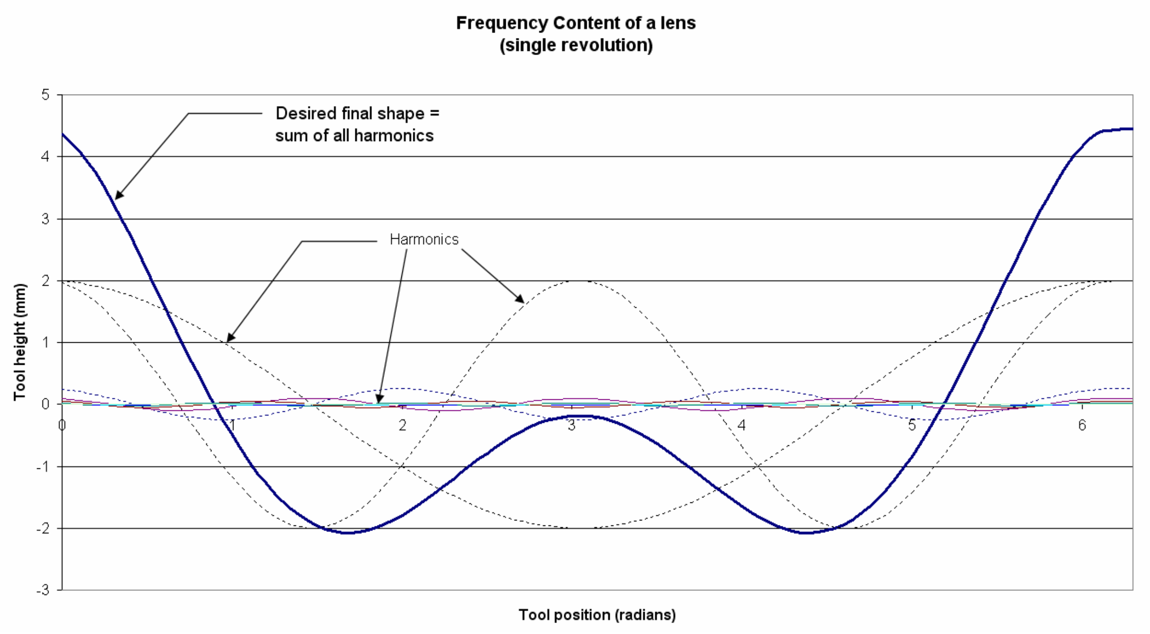

Figure 2

Even a simple toric lens cannot be represented by simple 1st or 2nd order harmonic as many assume. If one considers a general toric curve, the fundamental frequency (0th harmonic) can be considered as the rotational frequency of the lens spindle, the first harmonic of this is therefore 2X the fundamental frequency, and represents a first approximation of the general toric shape since it contains two cycles (bumps) per revolution. By decomposing this further one can see that the first harmonic alone is not sufficient to represent a toric curve, but that one needs to introduce much higher harmonics in order to minimize errors. This can be clearly seen by the following graph (figure 3).

Note from this graph that even at the 6th harmonic, errors are still above one micron. The practical implication of this can be understood when trying to spin the lens at a relatively high RPM in order to get more productivity from the system. For example, a rotational; speed of 3,000 RPM equates to 50 Hz (revolutions per second). If one needs to control tool position to the 8th harmonic (0.1 micron), then this implies you would need a fast tool system capable of at least 400 Hz bandwidth (50 X 8).

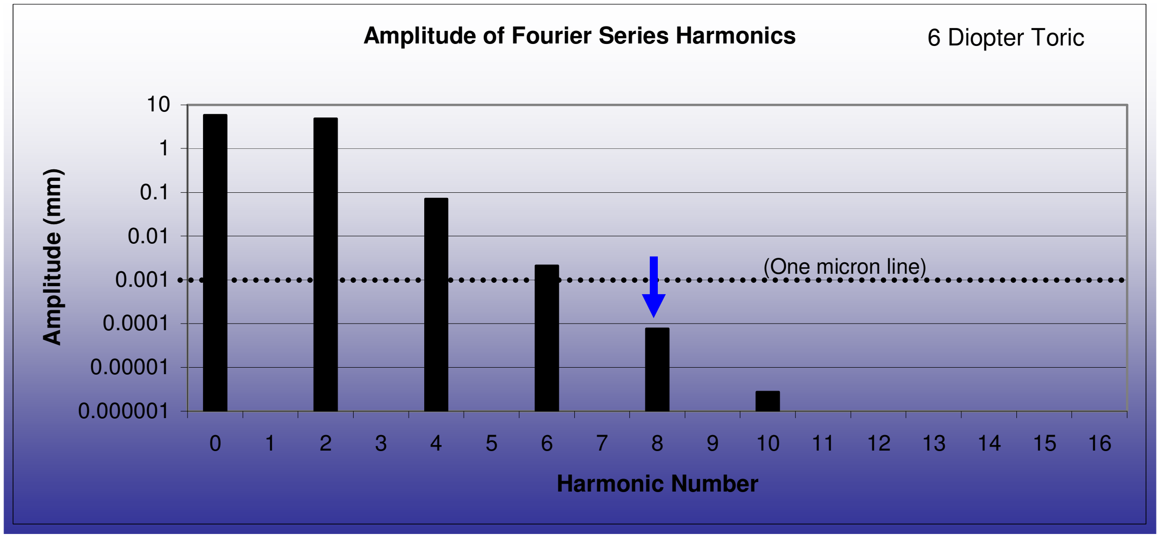

Figure 3

The next graph (figure 4) shows the frequency content of a typical progressive lens. From this, one can see the increased harmonic content and the implication this will have on machine performance. Notice that one needs to operate at or above the 15th harmonic in order to maintain errors below 1 micron, and the 26th harmonic for errors below 0.1 micron! The Satisloh VFT fast tool is capable of operating at these high harmonic numbers at high spindle RPM due to the exceptionally high bandwidth capability.

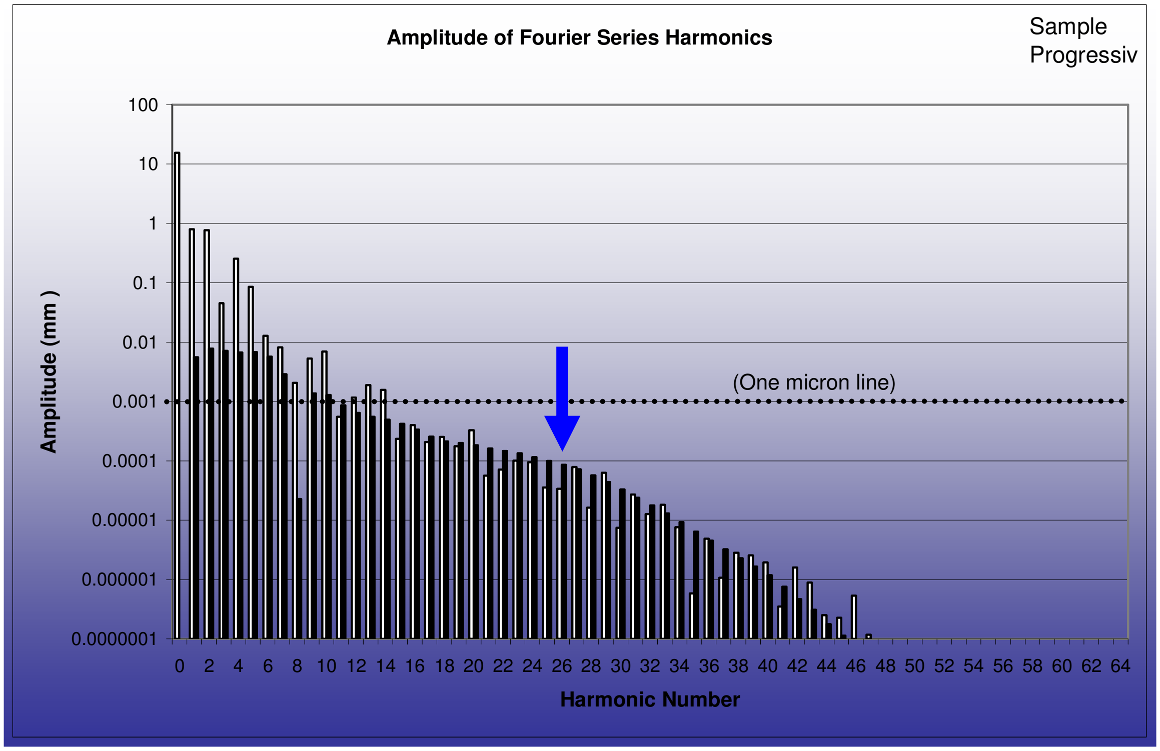

Figure 4

What is the result of insufficient bandwidth?

The following graphics illustrate what happens when the bandwidth is insufficient to include higher harmonics at the required working speed. Both figure 5a and 5b show a square wave as the desired shape to be followed. Figure 5a shows a 10th harmonic response whereas figure 5b shows a 100th harmonic. From this it can be seen that the higher harmonic (i.e. bandwidth) does a much better job of following the desired shape.

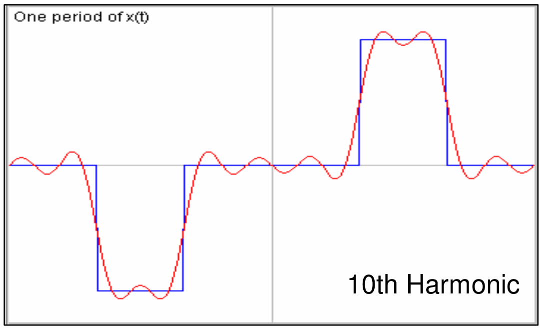

Figure 5a

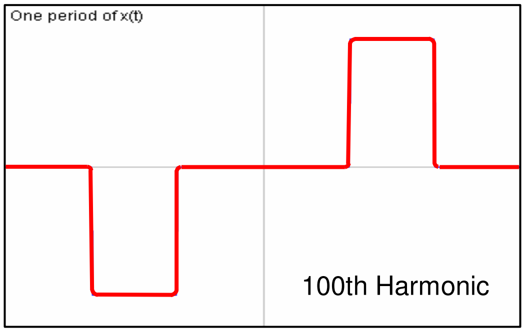

Figure 5b

This simple example shows that a lack of bandwidth results in a lack of form accuracy. So even a system with a high acceleration will produce a poor geometrical fit in the case of insufficient bandwidth. The practical implication of this in a low bandwidth generator is that one would need to either slow down the machine to the point where the errors become acceptable, or one could attempt to measure the errors and add a correction to the original data to compensate for these errors.

For better understanding try the interactive Fourier analysis applet at the following web site: http://www.jhu.edu/~signals/fourier2/index.html

Machine and Process robustness

Accuracy and high performance form a strong part of the lab requirements, however a good bottom line also requires machine and process robustness. Simply put, the ophthalmic laboratory wants a robust, easily controlled process delivered by a manufacturing system that is equally robust and reliable. In theory one can exist without the other, however this is not sufficient for successful implementation, and generally will not satisfy the requirements of the production lab.

Air Bearing Technology: Over decades LOH had acquired the reputation for making very robust, well designed machines. They have set the standard in the industry for machine reliability, and this has not changed with the merger between Satis and LOH. In fact, the new Satisloh has been taking steps to maintain and improve the quality of its machine designs. The new VFT machines use a ***zero friction air bearing*** based fast tool design that, in addition to providing the best in accuracy and bandwidth, was developed with special materials that make the system extremely ***"crash resistant***". Testing has shown that what would normally be a catastrophic crash when using standard rolling element bearings, the VFT machine has exhibited no perceivable negative effect to any of these critical bearings. Although a crash situation of this sort would likely destroy a lens chuck or tool holder, the extent of damage during testing was limited to these elements. No damage was seen to any of the critical bearings.

A heavy crash will typically slightly damage ball bearing guideways and / or balls. In conventional generators this may result in a major repair. Sometimes however it will go unnoticed since the slight surface errors resulting from the “rumble” of bumpy bearings will be polished out using hard laps and long polishing times. The bearing quality needed for high quality freeform work however is much more demanding than that of cut to polish. The Satisloh VFT crash resistant bearings are ideally suited to heavy and sustained production without the risk of reduced surface quality over time.

Voice Coil Actuators: In addition to crash resistant, ultra smooth air bearings; Satisloh has incorporated voice coil actuator technology into the VFT fast tool design. The reasons for this are again to achieve robust high performance, since voice coils are direct drive, hysteresis-free, cog-free devices offering high-acceleration and “clean”, error free motion. They deliver infinite position sensitivity, limited only by resolution of the feedback device. In addition, voice coil technology has been used for years in applications all over the world in semiconductor equipment, defense systems and life-sustaining medical systems, so its robustness is unparalleled.

What does all this mean for the end user?

Bottom line is ***accuracy and performance combined with process and machine robustness***. Many of our customers had been working with other equipment before purchasing their VFT machine(s) and some commented that they were amazed they no longer needed to “compensate” for form errors when they started using their VFT. In the past they had to either slow down the machine to a point where form errors became more acceptable, or else they had to painstakingly measure the errors, and adjust the data files to compensate for their machine’s inability to follow the correct curve. Slowing down the machine was ok for research activities, and high cost “premium” lenses, but this is totally unacceptable for a production machine.

By designing the VFT fast tool to have both low mass and high bandwidth, Satisloh has produced what are considered to be the highest performance freeform machines in the industry. When this is then combined with crash resistant air bearings, and the legendary LOH quality; the industry can now plan for, and start implementing the “radical” freeform changes that everyone has been anticipating.

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