**SUMMARY**
High end systems such as optical metrology, laser and lithography systems all require optical components with tight form and finish requirements. Precision polishing using pitch tooling is regularly used to obtain the part specifications. Pitch tooling consists of a metal platen covered with a layer of pitch. Pitch is a visco-elastic material that is typically derived from pine tree resin. Synthetic, polymer based versions are also available. To date limited data exists on the dynamic properties of polishing pitch and their impact on the polishing process. The work outlined here experimentally measures the steady-state response of pitch samples to forced vibrations of known amplitude and frequency. Pitch samples of varying hardness and thickness were tested. Samples are placed on a shaker table and tested at frequencies varying from 100Hz up to 8kHz. Load cells and accelerometers measure the dynamic response. Initial results demonstrate that below resonant frequencies, neither pitch type or thickness attenuated the source vibrations. Vibrations with nanometer level displacements were easily transmitted through pitch samples as thick as 25.4mm. The geometry of the pitch sample and the mass placed on the sample had a greater impact on the resulting dynamic response than the type of pitch used. These early results suggest that both the geometry of the pitch tool, and the mass of the workpiece being polished will impact the magnitude of the process vibrations transmitted through the tooling to the workpiece.

**BACKGROUND**
As stated, pitch tooling consists of a metal platen covered with a layer of pitch. Pitch is a viscoelastic material that is typically derived from pine tree resin [1]. Synthetic, polymer based versions are also available [2]. Abrasive particles embedded into the pitch surface during the polishing process enable both material removal and workpiece surface smoothening. Depending on the pitch tool size and pitch grade (hardness), a single pitch tool can have a life span ranging from two weeks to over a year. Over time pitch tool properties will vary, yet they remain relatively undefined and unmonitored when compared to the tools used in other material removal processes such as grinding.

Current pitch testing is crude and involves either operator experience or a basic indentation test that only captures the materials long term response [1][3]. No instrumentation exists to monitor the condition of the pitch tooling over its life span, and little scientific data exists to direct optimal tooling design. The current success of pitch polishing depends on highly skilled operators with years of experience. It is important to fully understand the pitch’s interaction with the polishing process if the process is ever to be deterministic and repeatable. An increased knowledge database on pitch and pitch tooling will result in a more repeatable and cost efficient process. Previous work by conducted by the main author begun to investigate new metrics. Impact frequency response testing was employed and details of how it can differentiate between pitches can be found in the following referenced papers [4][5]. The impact testing revealed that each pitch type (different grades and manufacturers) has its own unique resonant frequency and damping ratios. These results prompted an in-depth look at how pitch behaves under steady state dynamic conditions, i.e. how will it interact with process vibrations. Does pitch amplify or attenuate vibrations? The initial step of investigating the short term, steady state response is outlined here.

**EXPERIMENTAL SET UP**
Details of the equipment used, the samples tested, and the testing conditions are given in the following sections.

**Equipment**
Steady state testing of the pitch samples is done on a shaker table. See Figure 1 for a block diagram of the test set up. The shaker table, BK Vibration Exciter Type 4809, can oscillate up to
20kHz. It is driven by a HP Dynamic Signal Analyzer, HP35639A, and BK power amplifier, Type 2706. The dynamic signal amplifier can send both swept and fixed sine waves inputs to the shaker. The force experienced by the vibrating system is measured by an Omega dynamic load cell, DLC101-10 (0-10Lbs). Two PZB accelerometers (1 to 10kHz) measure the accelerations at the base and top of the test sample assembly. A National Instrument DAQ card, with a maximum sampling rate of 500KHz, collects the output data from the load cell and the accelerometers. The signals are recorded using PCScope™. This software package can also perform the double integration on the accelerometer readings to give the corresponding placements (X and Y). Additional data processing is done in MATLAB to calculate the displacement and force amplitudes. Prior to testing pitch samples, the dynamic response of the experimental setup was evaluated with the dynamic signal analyzer. The load cell output was sent to the signal analyzer and evaluated with respect to the driving swept sine wave input (100Hz to 11kHz). The system was found to be linear.

![FIGURE 1. Schematic of the main components used in the experimental set up.](image)

**Sample Preparation**

Two different grades of synthetic polishing pitch were chosen for these initial tests; Acculap™ Standard and Acculap™ Soft. Two different sample thicknesses were also selected; 25.4mm (mass=50g) and 11.9mm (mass=25g). A 100g mass was attached to the top of the 25.4mm thick sample, while a 125g mass was attached to the top of the 11.9mm thick sample. This was done so that the shaker would exert comparable forces on the samples tested. To make the samples the interface place, which attaches to the shaker, was placed in the bottom of a silicon mold. A defined mass of pitch was poured onto it to make the thick or thin sample. To pour the pitch it was first heated over a water bath until melted and then heated directly on the hot plate for 5 minutes to make it sufficiently fluid for easy metering into the silicon molds. While the pitch was still warm and compliant, the ‘top mass’ is embedded in the pitch. Fixturing prevented the top mass from sinking into the sample, or tilting significantly as the pitch cools. This method of sample preparation gave good pitch-metal interface bonding consistencies. See Figure 2 for a schematic of the sample. Samples were let cool over night before testing. Twelve samples in total were made, six thick samples which comprised of three Acculap™ Standard and three Acculap™ Soft samples, and six thin samples (three of each pitch grade).

![FIGURE 2. Schematics of the samples made for testing.](image)

**Testing Conditions**

Once mounted on the shaker table each sample was subjected to a swept sine wave (100Hz to 9500Hz). As before the load cell was connected to the dynamic signal analyzer and its response to the input swept sine wave recorded. The resonant frequency of the system (shaker and sample mass) for each sample was determined. As expected the thin samples all have a comparable resonance peak. The same is true for the thick samples. Any significant variation in a samples response from the averaged response implies that there was either misalignment within the sample,
or that there was poor bonding at one or both of the pitch-metal interfaces. The systems resonant frequencies with the thin and thick samples were 6713Hz ±105Hz (1 std dev.) and 6118Hz ±167Hz (1 std. dev.) respectively. Once the resonant frequency was isolated, two frequencies on either side of the resonant peak along with the resonant peak were identified for further investigation. Other points included for investigation were 100Hz, 200Hz, 1000Hz, and 3000Hz or 4000Hz. The load cell was reconnected to the DAQ card. A fixed sine wave at each of the above frequencies drove the shaker table and the response of the accelerometers and the load cell recorded. All twelve samples were evaluated with low and high amplitudes inputs. At low amplitude the shaker table displacement ranged from 1.5μm to 0.2nm while at high amplitude the displacements ranged from 15μm to 2nm.

RESULTS AND DISCUSSION

Figure 3 illustrates the ratio of displacement X to Y measured on the thin samples for different frequencies of the higher amplitude inputs. Figure 4 shows the same information plotted for the thick samples. The same trends as illustrated in Figure 3 and 4 were found when testing at the lower amplitude. Within the bandwidth tested, only the thick samples had a resonance peak.

At lower frequencies (<4kHz), well below any resonance peaks, the displacement ratio between the top and bottom of the samples was approximately equal to one for all samples. The practical implication of this is that neither pitch type nor thickness attenuates the input vibrations. Periodic displacements with peak to valley values as low as 1nm were transmitted through the pitch.
At the higher frequencies (>4Hz), it is clear that the geometry of the samples has more of an impact on the dynamic response of the pitch than the type of pitch used. At resonance (X/Y peaks) the input displacement was amplified up to 19 times as it travels through the thick pitch samples. Within the frequency range tested, the thin samples provided much less vibration amplification. The clear difference in the curves generated by the thin and thick samples is related to either the thickness of the pitch layer, or the change in the mass attached to the pitch. The thinner pitch layer is expected to have a higher associated stiffness than the thicker layer. An increase in stiffness effectively increases the resistance to deformation and the associated resonance frequency of the sample. If testing on the thin samples was continued beyond the 8000Hz, then resonance peaks as seen with the thicker samples should appear. Brown [1], in his paper on polishing pitch, noted that pitch thickness affects polishing outcomes. He focused on tool 'compliance', i.e. the flow of the pitch over several hours, in his explanation of the phenomena. The results presented here indicate that the pitch thickness can impact the shorter term dynamic response. This may also contribute to the differences observed between tools on the workshop floor. Additionally the thinner samples had a larger mass attached to them than the thick samples. The masses may act as passive dampers counteracting and negating system vibrations. Tests are being designed to clarify this point. Irrespectively, the results raise a practical consideration; how does the mass of the workpiece being polished affect the dynamic response of the system? A platen that polishes a large glass workpiece efficiently may not polish a smaller, lighter workpiece of the same material as effectively or indeed vice versa. Work is continuing in this area.

CONCLUSIONS
Even though these initial tests do not fully explain steady state polishing dynamics, they provide some interesting insights and topics worthy of further consideration.

Below the resonance, neither grade of polishing pitch or sample thickness provided any vibration attenuation. Even vibrations with nanometer level amplitudes were transmitted through the test samples. At resonance frequencies (peaks in Figure 4), both the Soft and Standard pitches amplified the source vibrations. Well above the resonance point (as seen with the Soft_3 sample in Figure 4) attenuation of the vibrations is evident where X/Y <1.

Both the sample geometry and the weight of the top mass, have a greater affect on the dynamic system response than the type of polishing pitch used. This has implications for tool design, i.e. the thickness of the pitch poured on the platen etc. The results also indicate that the dynamic characteristics of a polishing system/tool may not be optimal for all workpiece masses and sizes. Further work is continuing to better understand these considerations.

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