Material Characterization and Drilling Enhancement Through Stochastic Perturbation

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***Abstract*—Drilling is a common machining process used for creating regular holes in a diversity of solid materials. This project was designed and built to study the drilling process in detail - with the specific goal of characterizing materials in situ based upon the gain, natural frequency, and phase of their respective impulse responses. In order to achieve this, we tested six different materials (graphite, wood, wax, plaster, ABS, and aluminum) by perturbing the input voltage of the drill with a stochastic binary input, and further applying a Toeplitz matrix inversion to the measured voltage and current output of the drill. Simultaneously, we also measured the speed of the drilling process, in order to test the hypothesis that a binary stochastic voltage input could be utilized to achieve higher drilling efficiencies. Our results successfully showed the ability to differentiate amongst materials according to the aforementioned parameters of their impulse response; and further, that a stochastic input could be used to increase drilling efficiency. Though, notably, this increase in drilling efficiency was inconsistent amongst materials, with ABS showing the best results, and graphite, wood, wax, and plaster showing a dependence on the frequency of pulse width modulation of the input power. All of this information could potentially be used to design portable drills that could cut materials more efficiently and optimize feeds and speeds in real time based upon the drilled material - an especially useful feature for anisotropic materials such as sandwich composites in the aerospace industry or trabecular bone in the case of orthopedic surgery.**

Keywords—dither; drilling; material characterization

I. Introduction

One of the simplest and most common ways to create a cylindrical hole in a piece of solid material is by drilling [1]. A drilled hole is cut from the material by pressing a rotating fluted drill bit into the surface. Drill bits come in many sizes and geometries for different applications, but almost always drive a hole of a circular cross-section. Material is removed at the tip of the drill bit and chips escape by traveling along the flutes towards the top surface of the material [2][3]. Bits are connected to mechanisms that rotate them and provide the necessary torque and axial force. Mechanisms include machine tools such as CNC milling machines, drill presses, hand-held battery powered drills, or hand-held mechanical drills. Here, we modified a handheld drill and used system identification techniques to better understand drilling.

Two key parameters left to the user are the selection of feed (axial advancement) and speed (rotation) of the bit. Information about appropriate feeds and speeds often requires many hours of experience, consultation with a professional technician, or exploration in a mechanical handbook [4]. Currently, commercial drills do not have the capability to automatically adjust feeds and speeds for the given material being drilled, and efficient cutting is therefore left to the user's experience level. In an effort to improve drilling efficiency, and to remove the skill and experience required of the user to properly drill into a material, a study was performed to investigate if materials could be characterized by their response to drilling with the potential to use these characterizations in future iterations to optimize feeds and speeds according to these responses.

We applied system identification techniques to model the responses of various materials based on specified drilling inputs. We hypothesized that different materials would have different characteristic impulse responses depending on their mechanical properties (i.e. hardness, yield strength) and microstructure, and ideally, that unique responses could be used as a closed-loop feedback mechanism for drill control and improved efficiency. Additionally, while other work has focused on minimizing drilling vibrations [1], some studies have demonstrated that required cutting force can be reduced by introducing vibration [5][6]. Therefore, we assess if adding a binary stochastic modulated drilling signal can produce higher cutting efficiencies.

II. Methods

A handheld drill was modified so that the drill motor voltage input could be modulated, and the power required to cut the material was measured. System identification techniques were applied to characterize the impulse response function of the drilled materials.

A. Mechanical Design of Experiment

A Ryobi 18V handheld drill was immobilized onto a 500 mm x 600 mm piece of plywood using zip ties. Constant force springs of 47.2 and 110.3 N (McMaster Carr) were mounted in pairs to provide a total of 94.4 or 220.6 N of force, with 220.6 N used only for aluminum. The springs were fixed concentrically around two bolts that were fastened into the plywood and symmetric about the cutting axis of the drill. Teflon disks were placed between the bottom edge of the springs and the upper face of the plywood to minimize friction. Similarly, nylon bushings were placed between the inner face of the springs and the outer face of the bolt.

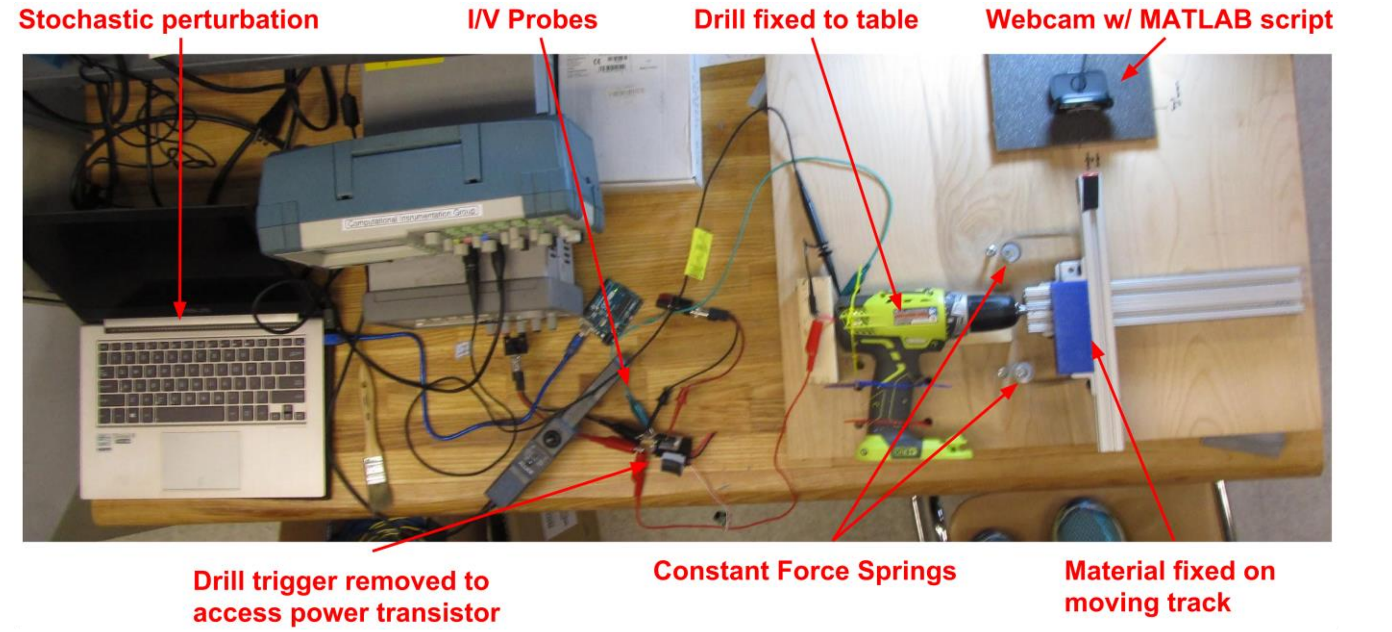

Figure 1: Photograph showing the mechanical system for drilling a straight hole in a material. A handheld drill was attached to a mechanical fixture that pushed the drill into the material at a constant force. A webcam tracked over time the displacement of the material relative to the drill

In line with the bolts were two aluminum 80-20 T-slotted extrusions fastened to the plywood. Connecting the two pieces was a perpendicular linear bearing which fit into the T-slotted frame. Here, a 30 mm x 30 mm x 200 mm rectangular block of the respective material (pine wood, wax, plaster of Paris, graphite, aluminum, and ABS) was placed and immobilized with two side brackets which fit into the bearing. The springs were mounted onto the linear bearing using angle brackets.

At the side of the setup, a webcam was placed approximately 200 mm away from the material, facing normal to the sliding/cutting axis. The webcam was taped onto a polystyrene foam which served to damp vibrations coming from the drill.

Finally, a steel dowel was placed in the board to prevent the slider from sliding when experiments were not being run. At the beginning of each experiment, the steel dowel was removed from the board and the constant force springs were free to pull on the material.

B. *Electrical Design of Experiment*

The circuit shown in Figure 2 controls the voltage across the motor of the Ryobi 18V handheld drill, thereby controlling the power output of the drill. This task is accomplished with an Arduino Uno that outputs a 490 Hz PWM waveform with either a fixed or a varied duty cycle to the gate of a STP75NS04Z N-channel power MOSFET, which was removed from the drill trigger. Tektronix P2220 passive 1x/10x voltage probes, set to 1x attenuation, were used to measure the input PWM waveform and the voltage across the drill motor. A resistive voltage divider was set in parallel to the drill motor to

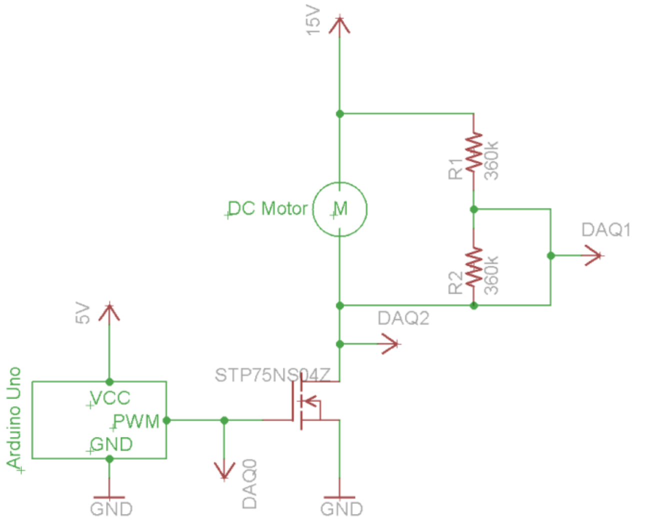

Figure 2: Circuit schematic illustrating a power transistor interfacing the drill motor and an Arduino Uno, which provides an input waveform that controls the motor voltage in time. Voltage and current measurements are sampled in locations labeled 'DAQx'.

keep the sampled voltage below maximum ratings. To measure motor current, a Fluke 80i current probe was used which outputs a voltage at 100 mV/A. All measurements were sampled at 5 kHz by a 4-channel National Instruments cDAQ-9174 and recorded using LabVIEW. In this setup, the drill battery was removed and the drill is powered by an HP E3632A DC power supply, capable of supplying up to 7 A at 0-15 V.

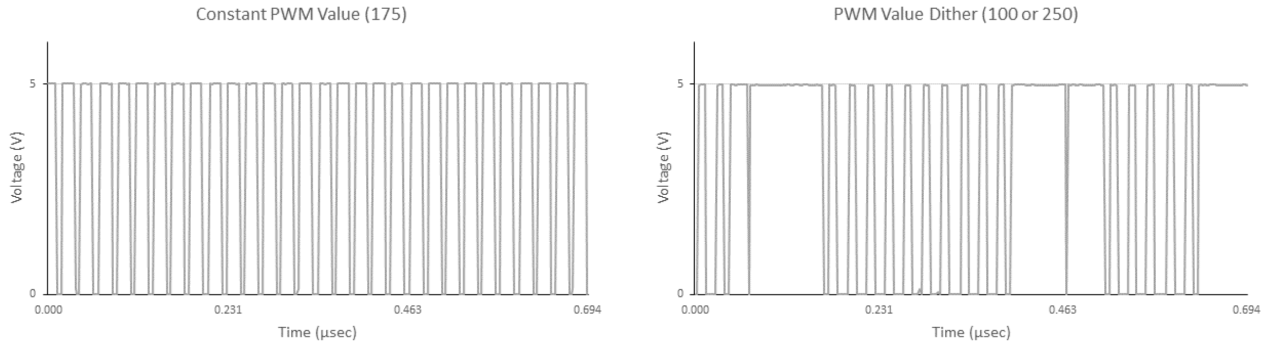

Figure 3: Illustrations of constant duty cycle input waveform and dithered duty cycle input waveform.

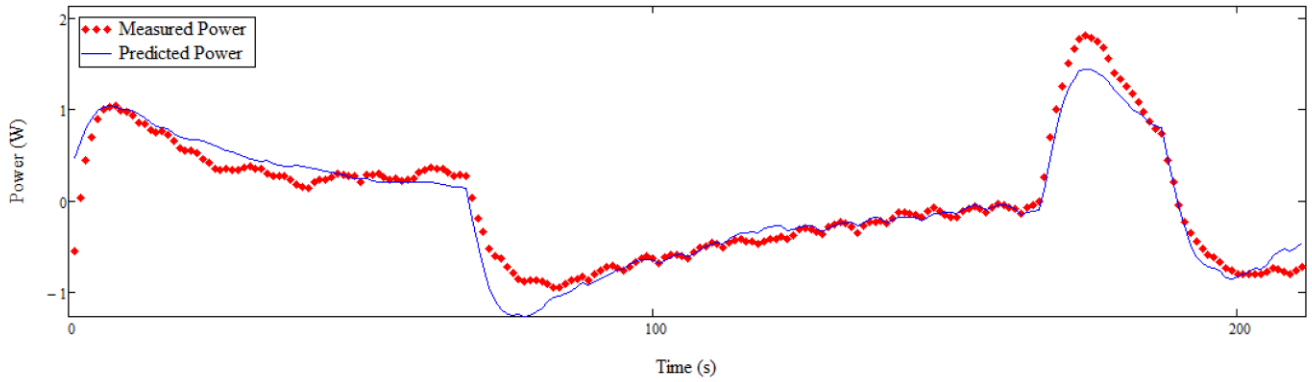

Figure 4: Measured and predicted output powers are shown for an aluminum sample with 5 Hz stochastic binary input; the Variance Accounted For is 91%.

C. System Identification Techniques

The drill motor was driven by several different input waveforms: (1) 490 Hz PWM with constant duty cycle, named “no dither” or (2) 490 Hz PWM with binary stochastic duty cycle (“dither”), where the duty cycle value was randomly determined to be one of two values at a rate of 5 Hz, 10 Hz, or 100 Hz. On the Arduino Uno platform, duty cycle is represented by an 8-bit integer (0-255), where 0 and 255 represent minimum power and maximum power for the drill, respectively, with a linear relationship between duty cycle and power for the intermediate values. For the constant duty cycle input, a value of 175 was chosen throughout the experiments. For the dithered input, a uniform random number generator function set the duty cycle to either 100 or 250 every 10 ms, 100 ms, or 200 ms - corresponding to the 100, 10, and 5 Hz trials, respectively. These duty cycle values were chosen so that over the duration of the experiment, both the constant and dithered inputs would be expected to result in equal power consumption by the drill. The two input types are illustrated in Figure 3.

For measuring the velocity of the material through the drill bit, the webcam was connected to a computer loaded with a MATLAB script. The MATLAB script identified a rectangular piece of red tape attached to the side of the block of material, and tracked the center of the red tape throughout the experiment at a sampling rate of five frames per second.

Voltage and current data were recorded by the National Instruments cDAQ at 5 kHz and included both the effects of the PWM signal at 490 Hz, as well as the dithered binary stochastic input at 5, 10, or 100 Hz. Data was first truncated to remove the transient effects at the start of drilling and to focus on steady-state drilling.

In order to demodulate the effect of the 490 Hz PWM signal from the response of the drill, input voltage and output power were both averaged for each period of the PWM signal. In doing so, the step changes in the PWM were identified by a threshold voltage change – a drop of more than 2 volts, representing 40% of the signal range. At each step down, the subsequent 10 data points were numerically averaged and exported as the demodulated signal. This demodulated signal was ultimately used for determining the impulse response function for each material as it was drilled.

The demodulated power signal was first numerically convolved with a low-pass filter with cutoff frequency of 1000 Hz. The low-pass filter removed some of the more extreme noise resulting from the brushes coming into and out of contact with the motor.

Following the filter, the demodulated input voltage signal (input) and demodulated power signal (output) were numerically shifted down, such that each signal had a mean of zero. The auto-correlation function for each signal was calculated as well as the subsequent cross-correlation function. The impulse response function was estimated via Toeplitz matrix inversion and deconvolution of the input auto-correlation function from the cross-correlation function.

The estimated impulse response function was validated by the convolving it with the input signal and comparing the predicted output with the actual. The Variance Accounted For (VAF) between the output and prediction serves as a metric for the accuracy of the estimation. The VAF across materials was strongest with the binary stochastic signal at 5 Hz, with an average of 89%, suggesting a strong predictive capability to model the materials as linear systems, as shown in Figure 4.

III. Results

The impulse response functions for each material tested, shown in Figure 5, were generated using a Mathcad script and the system identification techniques aforementioned. These responses were determined using the demodulated input voltage and demodulated output power signal. It should be noted that only one data set per material is represented in Figure 5. While difficult to draw conclusions or significant differences in responses for each material based on Figure 5, by fitting the impulse response to a standard second order transfer function we begin to identify differences in characteristic parameters across materials. The fit to the canonical second order transfer function was performed both with 1/5th and 1/10th of the data sample set, so as to focus impulse response fitting on maxima of each material, rather than the tail end of the impulse response. For each sampling size, the resulting undamped natural frequency and DC gain for each material's impulse response is presented in Figure 6. These parameters suggest that different materials respond differently to a given drilling input.

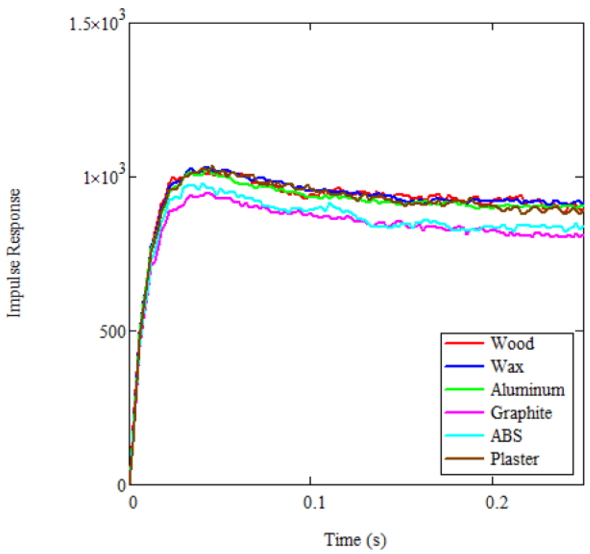

Figure 5: Inverted impulse response function for the six materials tested at 100 Hz.

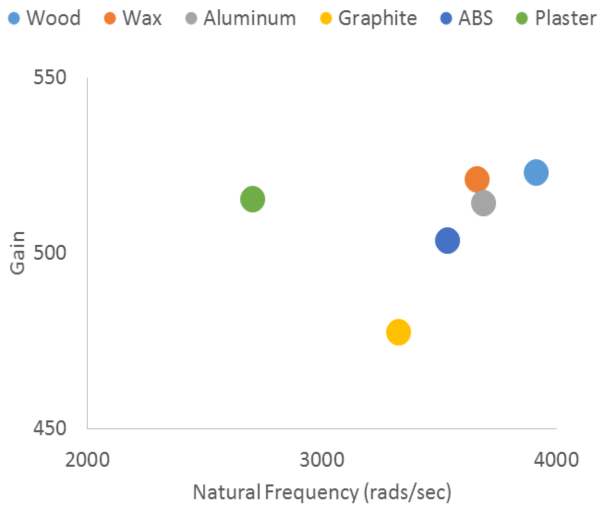

Figure 6: Impulse response parameters (gain and damping frequency) across materials for the first tenth of the data.

Additionally, cutting efficiency was assessed via power-normalized drill speed data into each material, which was captured via the webcam and MATLAB image tracking script. Drill speed for each material was further normalized by the no dither case, and compared across materials and tested dither frequencies, as shown in Figure 7. We observed that stochastically perturbing the input to the drill motor resulted in a difference in cutting speed, and that cutting speed can be improved using the appropriate frequency for all materials except aluminum.

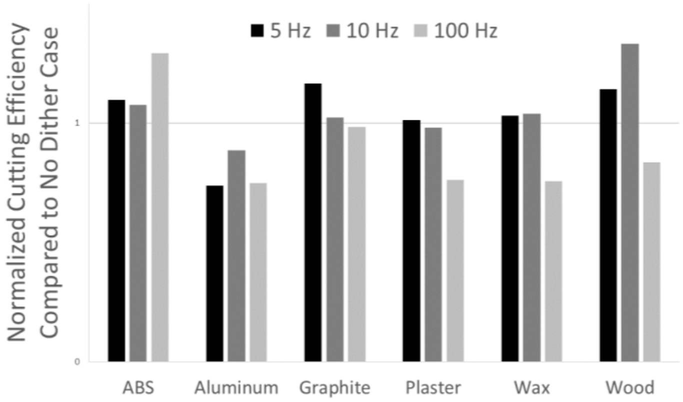

Figure 7: Normalized cutting speed for 5 Hz, 10 Hz, and 100 Hz frequencies across all materials.

IV. Conclusion

The work reported here shows the feasibility of modulating a handheld drill's input voltage and - through system identification techniques - determining the impulse response function of the material being drilled. Preliminary experiments have successfully modeled the impulse response for a range of six materials and have identified differences in responses across these materials. Additionally, some materials have shown an increase in power-normalized drilling velocity in response to a stochastic binary input of varied frequencies. This improvement and corresponding modeling potential show a clear need for further study and consideration.

V. Future Work

Future design iterations will place emphasis on portability for the home user, as shown in Figure 8. In order to increase efficiency of a drill using perturbation, knowledge of the motor voltage and current, as well as the force applied on the drill are needed. A force sensor with a range of up to 500 N will be placed opposite the drill trigger where the palm of a user presses against the drill. The force sensor will be wired to a circuit board that is located below the drill battery. In addition to reading the input from the force sensor, the circuit board will probe both the current and voltage used by the motor. The circuit board will also create the necessary voltage regulation to perturb the drill. Measurements of current and voltage will be communicated over Bluetooth to a local computer for further analysis, the results of which will be communicated back to the drill and displayed on an LED screen. We have already begun to prototype this design, which is shown in Figure 9.

Figure 8: Future design iteration that emphasizes portability. Arduino or similar microcontroller and electronics are attached on outside of drill and in protective casing.

Future work will be further dedicated to understanding the fundamental material properties related to the material removal rate associated with drilling. Much like an Ashby plot, we hope to develop a material performance parameter, potentially taking into account material properties such density, fracture toughness, and yield strength - and correlate that to our resultant gain versus natural frequency charts to validate our experimental results from theoretical standpoint.

Figure 9: Photograph of prototype portable drill with stochastic perturbation.

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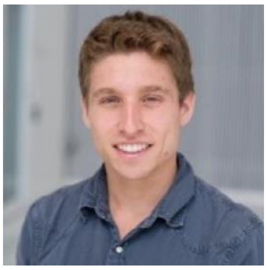

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