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A new test bench system for hammer drills: Validation for handle vibration

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ABSTRACT

Workers' can be exposed to high levels of hand vibration when drilling into concrete or rock using hammer drills; exposures that can cause hand arm vibration syndrome. Exposure levels may be reduced by different drill and bit designs and drilling methods, but these interventions have not been systematically evaluated. The purpose of this project was to develop a robotic test bench system for measuring handle vibration on drills in order to compare differences in drill designs, power sources, bit designs and drilling methods. The test bench is a departure from the ISO method for measuring drill handle vibration (ISO 28927-10), which requires drilling by humans. The test bench system was designed to repeatedly drill into concrete blocks under force control while productivity and handle vibration were measured. Handle vibration levels with different drills and bit sizes were similar to those collected following ISO methods. A new robotic test bench system for measuring handle vibration is presented and validated against ISO methods and demonstrates dynamic properties similar to human drilling.

1. Introduction

Drilling into concrete with hammer and rock drills is a physically demanding task associated with exposure to hand vibration, noise, silica dust and high hand and arm forces. Typical hand vibration levels are 8–16 m/s^2 for hammer drills and 14–20 m/s^2 for pneumatic rock drills (frequency-weighted acceleration levels per ISO 5349-1) (Griffin et al., 2006). These exposure levels can cause hand arm vibration disorders after months of exposure to many hours of exposure per week (Palmer et al., 2000; Edwards and Holt, 2006).

Drilling holes into concrete is a common task in commercial construction required for placing anchor bolts to support pipe, conduit, ducts or machinery and for setting rebar (e.g., dowel and rod drilling) for structural retrofits, seismic upgrades or extending roads and tarmacs (Fig. 1). Recent examples of large jobs in Northern California were (1) a highway sound wall upgrade in Northern California required 25,000 1″ diameter, 12″ deep holes drilled with 30 lb rock drills; (2) seismic upgrades to all Bay Area Rapid Transit (BART) train towers, each tower required 800 1″ diameter holes 18″ deep, (3) a 6″ conduit hung from the ceiling of a 5 mile tunnel required 13,000 5/8″ diameter holes, and (4) a commercial building remodel in San Francisco required 40,000 3/4″ diameter holes. In the US, concrete drilling is done by laborers (697,980), brick and block masons (56,590), cement masons (143,250), carpenters (516,340), electricians (424,810), and plumbers (304,480) and drilling into rock is done by miners (51,810) [BLS and National Industry-Specific Occupational Employment Estimates 2014].

Handle vibration levels when drilling into concrete can be reduced with a drilling rig (Rempel and Barr, 2015). Other interventions may also reduce handle vibration. For example, new high torque electric hammer drills may have lower handle vibration levels compared to the equivalent weight pneumatic rock drills. Dampening systems that are integrated into the drill handle may reduce handle vibration. Drilling with different feed force may change the handle vibration profile. Drill bit design or bit wear may alter handle vibration. However, the effects of these designs and drilling methods on handle vibration have not been systematically evaluated.

Automated test bench methods have been developed for evaluating silica dust exposure from cement cutting tools (Heitbrink and Bennett, 2006; Akbar-Khanzadeh et al., 2010; Meeker et al., 2009). However, automated bench methods have not been developed for measuring handle vibration with hammer drills and there are no international standards for such test bench systems. Instead,

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Fig. 1. Manual drilling with pneumatic rock drill for structural work.

international standards for measuring handle vibration require workers to drill into concrete under controlled conditions (ISO 28927-5; ISO 28927-10). Variance between subjects may be high with this approach due to differences in drilling technique. On the other hand, a test bench system may constrain the drill in ways that alters handle vibration as compared to drilling by workers.

The purpose of this project was to develop and evaluate a new automated test bench system for concrete drilling in order to compare handle vibration under different drilling conditions. Handle vibration measures from the new automated system were compared to handle vibration with workers drilling following ISO methods. The null hypothesis was that there were no differences in handle vibration levels between holes drilled using the test bench method compared to the ISO method.

2. Methods

2.1. Design of test bench system

A test bench system was designed and built with the following features: (1) automatically controls an active hammer drill and advances it into concrete under force control, (2) automatically advances concrete blocks after each hole is drilled, (3) accommodates a wide variety of drill types, (4) has similar dynamics to human dynamics, and (5) continuously records handle vibration during drilling. The drill is firmly coupled to a saddle that is moved horizontally by a linear actuator under feed force control (i.e., linear force or weight on bit). The drill saddle is coupled to a single axis load cell (Bertec, Columbus, Ohio) with a stiff spring aligned to the drilling axis (Figs. 2 and 3). The load cell, drill saddle and drill are moved on a lathe bed by a linear actuator. Non-reinforced concrete blocks (3.5 × 12 × 12?) are made consistent with reinforced structural concrete (slump 80 mm; EN 206-1:2000) and ISO standards (ISO 679; ISO 28927-10). Concrete blocks cure for at least 28 days before being used.

The drill is secured to the saddle with ring clamps at the drill handle. Closed cell foam-rubber (1 cm thick) is inserted between the clamps and the drill handle. The stiffness properties are similar to palmar skin; the foam compresses 25% of original thickness at 12 psi. The chuck rests on a support padded with the same rubber/foam.

A tri-axial accelerometer (Larson Davis SEN040F) is attached to the drill handle using hose clamps and the acceleration measurements are averaged with a vibration meter (Larson Davis HVM100)

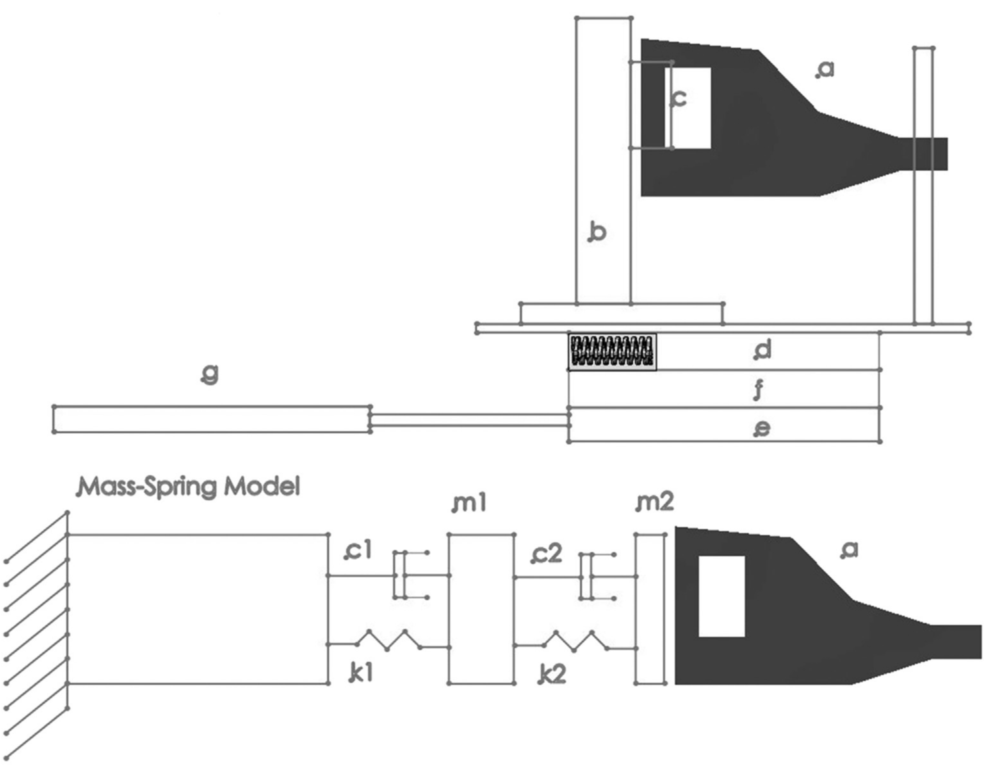

Fig. 2. Drawing of test bench system and corresponding mechanical mass-spring model with a hammer drill (a). The drill handle is clamped to a fixture (c) with rubber-foam between the clamp and the handle. The chuck rests on a rubber-foam support. In the model, m1 includes plate d, vertical bar b, and fixture c; k2, m2 and c2 are the rubber-foam interface. The stiff spring is k1; dampener c1 is the friction between d and f. The linear actuator (g) drives the whole assembly toward the concrete block.

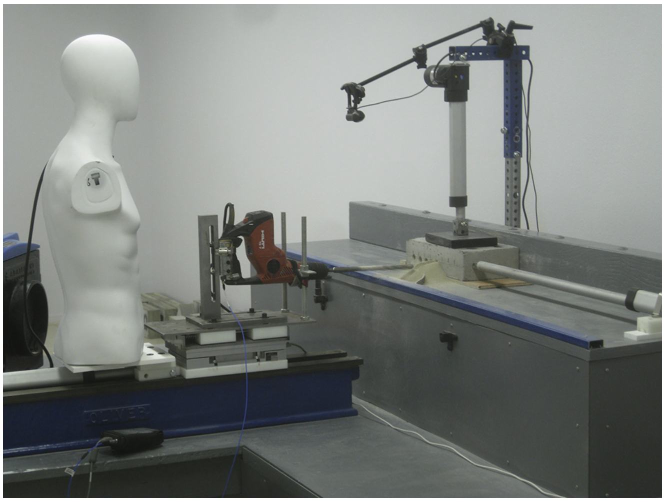

Fig. 3. Test bench system with a Hilti TE7 drill. Drill handle is secured to a vertical bar with hose clamps with rubber-foam between the clamps and handle. After each hole is drilled the concrete block is released and the block is advanced and secured for the next hole. The mannequin is located above the linear actuator and is positioned for noise and dust sampling.

and stored to a computer at a rate of 1 Hz. The accelerometer and vibration meter are calibrated prior to use (PCB Piezotronics shaker 394C06). The vibration meter applies a frequency weighting as specified by ISO 5349-1. Tool handle vibration acceleration magnitudes are interpreted according to ISO standards (ISO 28927-10).

The drill is activated manually with a strap around the trigger then advanced into a concrete block at a constant feed force (adjustable range: 50 and 500 N). It is automatically withdrawn after a specified depth is reached (adjustable up to 250 mm). After each hole is drilled, the concrete block linear actuator clamp is released, the concrete is advanced with another linear actuator, the clamp is activated to secure the block again, and the next hole is drilled. The system is controlled by a custom LabView program running on a PC. Productivity is measured as drilling time from first contact of the bit on the concrete to completion of drilling depth.

2.2. *Validation of system*

Validation was assessed by comparing feed force and handle vibration levels on the test bench system to the same outcomes from 4 experienced construction workers manually drilling following ISO methods. The study was approved by the University Committee on Human Research and subjects signed a written consent form.

Four test conditions were evaluated on the test bench: two electric hammer drills (Hilti models TE40 and TE7) each with a new 3/8″ and 3/4″ concrete bit. For each test condition, a minimum of 10 holes were drilled to 125 mm (ISO 28927-10) with a target feed force of 90N.

Two test conditions were evaluated by the human studies; the same two electric hammer drills with the 3/8″ bit. Subjects drilled 5 holes vertically into concrete blocks for each test condition while they stood on an electronic force plate with force sampled at 25 Hz (Acculab Digital Scale, Bradford, MA). Force plate output was adjusted to record feed force and the feed force was recorded in accordance with ISO standards. Subjects were instructed to apply feed force similar to their usual drilling. Handle vibration measurements were frequency-weighted acceleration as specified by ISO 5349-1 and were similar the test bench system methods.

Summary measures for handle vibration are presented as mean and peak values (m/s^2). Outcome measures between the test bench system and the ISO method are compared statistically using ANOVA with $p < 0.05$. Outcome measures between test conditions on the test bench are compared using ANOVA.

3. Results

The findings for the 4 drilling conditions evaluated on the test bench and the 2 conditions performed by workers are summarized in Table 1. For the 3/4″ bit, feed force for the test bench was close to target force of 90N with low variance for both drills. For the 3/8″ bit and small drill (TE7), feed force was close to target force but variance was high, while for the large drill (TE40) feed force was below target force. The self-selected feed force by workers was somewhat less than the target feed force used for the test bench but the differences were not statistically significant (TE7, $p = 0.59$; TE40, $p = 0.60$). As expected, the coefficient of variance (CV) for feed force for the workers was higher (CV = 0.05 to 0.28) than the test bench (CV = 0.02 and 0.11).

The test bench system demonstrated large differences in productivity (i.e., drilling time) between drills and bit sizes (productivity was not recorded during worker drilling). The larger drill completed 3/4″ diameter holes in 41% of the time compared to the smaller drill.

Mean vibration levels were not significantly different between the test bench and the human testing (TE7, $p = 0.34$; TE40, $p = 0.21$). Peak vibration levels were similar between the test bench and the human testing for the small drill (TE7, $p = 0.88$) but not the large drill. For the large drill, peak levels were lower on the test bench (TE40, $p = 0.0001$).

When comparing results within the test bench there were significant differences between test conditions on feed force, drilling time and vibration levels. Feed force for the TE40 drill with a 3/8″ bit was significantly less than all other test conditions ($p < 0.0001$). However, no differences in feed force were observed between the two drills for the 3/4″ bit ($p = 0.60$) or between the two bits for the TE7 ($p = 0.61$). Drilling time was significantly different between all test conditions ($p < 0.0001$). Both mean and peak vibration levels

Table 1
Comparison of mean (standard deviation) feed force and handle vibration between the test bench and human testing under different test conditions.

Drill	Bit	Feed force (N)	Drilling time (s)	Peak vibration (m/s^2)	Mean vibration (m/s^2)
Test bench					
TE40	3/4″	90.2 (3.8)	32.7 (1.4)	17.0 (2.0)	7.2 (0.5)
TE7	3/4″	89.7 (1.8)	78.8 (4.0)	29.1 (1.6)	9.0 (0.3)
TE40	3/8″	73.3 (4.3)	13.5 (0.6)	16.2 (2.1)	7.1 (1.1)
TE7	3/8″	88.5 (9.5)	15.2 (1.1)	31.1 (0.6)	9.5 (0.2)
Human testing					
TE40	3/8″	74.6 (4.1)		24.4 (1.6)	7.9 (1.0)
TE7	3/8″	81.6 (23)		31.5 (5.3)	10.1 (1.0)

were significantly different ($p < 0.0001$) between all test conditions except between the 3/8″ and 3/4″ bits on the TE40 drill.

4. Discussion

The test bench feed force was well controlled with low variance for the 3/4″ bit with both of the drills. The lower than expected feed force for the 3/8″ bit with the large drill (TE40) was likely due to the bit being undersized for the drill leading to poor feed force control. The larger variance in feed force for the 3/8″ bit on the small drill (TE7) may be due to a target feed force that is too high for this size bit and drill. Future testing should evaluate lower feed forces than 90N for a 3/8″ bit.

The similar handle vibration measures between the test bench system and human testing indicates that the dynamics of the test bench is similar to human dynamics. The test bench fixture was coupled to the drill handle with a foam-rubber of similar density and stiffness to the palm. In addition, a spring isolated the drill from the linear actuator, mimicking the stiffness of the forearm and upper arm. In general, the system mechanics were similar to the human arm (Dong et al., 2008, 2010). Future validation studies should evaluate larger bits and drills of larger mass and different power sources (e.g., pneumatic vs. electric).

The test bench method differs from the ISO 28927-10 method for handle vibration measurement in several ways. One difference is that the ISO method calls for drilling downward. However, when drilling downward with an electric hammer drill, the bit will bind if the dust is not removed. So drilling on the test bench is done horizontally to prevent bit binding. Furthermore, in the real world, structural drilling (e.g., dowel and rod) is primarily done horizontally. This difference with the ISO standard is not likely to impact study conclusions.

The most important difference between the test bench and ISO methods is that the ISO method requires the use of humans for testing. Human testing should produce grip and feed forces that are similar to real work. However, as demonstrated in this study, there can be large differences between subjects with human testing while the robotic test bench system minimizes variance. The problem of the robotic system not necessarily matching real world grip and feed force can be addressed by using the robotic system to systematically test different grip and feed forces. Since the robotic system can more precisely control these factors and can test a large set of conditions, the robotic system may provide greater insights into the effects of subtle differences in drill design and use on handle vibration. However, drill handle vibration levels on the test bench will be influenced by the dynamics of the system; therefore, test bench results should be interpreted with caution. For example, the tests were conducted over a relatively narrow range of vibration levels; the test bench dynamics may deviate from human dynamics at other vibration levels. In the long run, a test bench system is likely to compliment but not altogether replace human testing.

With the test bench system there were differences in drilling time between the large and small drill for the 3/4″ bit. Productivity measures are useful to contractors for cost estimation. In addition, differences in drilling time may be useful in estimating allowable exposure durations based on ISO and ACGIH limits for different handle vibration levels. The test bench system provides a reliable feed force compared to human testing, and, therefore, more precise measures of productivity.

A new test bench system for evaluating handle vibration on hammer drills was designed and built, following, to the extent possible, the ISO method. A validation study demonstrated comparable results with human testing indicating similar dynamics to the human hand arm system. Further studies should validate the system with drills and bits of different size and energy sources.

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