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Assessment of Hand Vibration Exposure on an Assembly Line

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This paper describes a study undertaken to evaluate and control vibration exposure associated with pneumatic screwdrivers used in an electrical appliance assembly plant. The study was motivated by management's concern about reports of cumulative trauma disorders in the upper extremities of workers who used pneumatic screwdrivers. Vibration exposure from power hand tools on an assembly line is difficult to predict due to highly variable conditions and techniquies used between operators. Vibration exposure was measured using observation samples of tool vibration obtained on the assembly line for individual assembly tasks. Typical tool one-third octave band acceleration spectra estimated from laboratory measurements were used in conjunction with the measured exposure times to compare workers' risk of exposure to the hazards associated with operating vibrating hand tools. Characteristic vibration produced by the tools during phases of operation were separated and analyzed individually to identify and control the source.

Introduction

This investigation is concerned with the evaluation and control of workers' exposure to vibration from hand-held power tools. The study was performed in an electrical appliance assembly plant where workers used small in-line hand-held pneumatic screwdrivers extensively to perform highly repetitive tasks on an assembly line. Cumulative trauma disorders were a major cause of lost time and workers' compensation at the facility.

Research has shown that prevalence of cumulative trauma disorders is correlated with vibration exposure.[1,2,3] Accurate estimation of daily vibration exposure for individual workers on the production line is difficult because of the highly variable operating techniques used between operators and anomalous contributors common to this operation such as cross threaded screws and back-up of co-workers who have fallen behind. Thus vibration exposure was assessed by sampling directly the vibration produced from the specific tools of individual operators and prediction of daily exposure using in-plant data.

Background

The term "vibration syndrome" is often used collectively for the symptoms associated with prolonged and repeated exposure to hand tool vibration. These symptoms include vasomotor irregularities, bone alterations and joint deformations, neurological disturbances, and soft tissue damage such as changes in the chemical composition of the blood.[4]

The condition known as "Vibration Induced White Finger," "Traumatic Vasospastic Disease" and "Raynaud's Phenomenon of Occupational Origin" is a disease of the fingers and hands with both neurological and peripheral vascular symptoms. The Taylor and Pelmear classification system[5,6] of the hand and arm condition is based primarily on a patient's medical history of attacks of vibration white finger rather than objective data. This is due to the lack of a conclusive and individually discriminating objective test for the disorder. Epidemiological evidence has shown that there is a positive correlation between the total time of exposure and the severity of vibration white finger, which suggests that the traumas are cumulative.[1]

Bone deformity is another of the lesions caused by vibration exposure. Radiographic studies of the wrist, elbow, shoulder and the cervical vertebrae of workers with weakened grip revealed abnormal findings in the elbows.[7] Kumlin *et al.*[8] observed vacuoles in the carpal and metacarpal bones and phalanges in workers who had been exposed to chain saw vibration over long periods of time.

Neurological disorders, such as disturbances in the sense of touch, increased sensitivity to cold, as well as ulnar paresis and paralysis, acroparesthesia accompanied by cramp-like pains in the extremities, and fatigue have been observed in workers exposed to vibration.[4,9] Abnormal findings in nerve conduction velocity studies have been reported when symptoms of parasthesia, numbness and or pricking sensation were present in workers who had used vibrating tools for several years.[10]

Rothfleish and Sherman[11] have attributed the incidence of carpal tunnel sydrome to the use of vibrating hand tools and to the position of the hand and wrist during the performance of work.[11,12] Carpal tunnel syndrome is usually attributed to compression of the median nerve.

Segmental vibration exposure limits have yet to be adopted in most countries including the Unites States. The International Standards Organization (ISO) exposure guidelines for hand-transmitted vibration[13] is a provisional concensus standard based on data from both practical experience and laboratory experimentation derived primarily from subjective human response to hand-transmitted vibration and mechanical behavior of the hand-arm system. The ISO guidelines are specified in terms of vibration acceleration, daily exposure time and direction of vibration relative to the hand. Exposure zones for hand-transmitted vibration are recommended for regular daily occupational exposure over long periods of time in terms of acceleration measured in one-third octave band spectra.

Insufficient dose-response data are available to correlate the exposure zones with degree of risk of incurring vibration-induced diseases in an average worker population. Thus, they do not assure limits of safe exposure but provide a bench mark with which tools may be compared.

Study Site

The factory considered in this investigation produces small electromechanical appliances. A typical production line representative of plant manufacturing operations was used for study purposes. Twenty-three workers were employed in the assembly operation where seventeen of these positions required the use of pneumatic screwdrivers. One position necessitated operation of two screwdrivers. The production rate was 2.9 units per minute which was below average with a production rate of 3.2 units per minute considered to be typical for the line. Five workers were new and inexperienced. Three additional workers were positioned on the line to back up the trainees.

The screwdrivers used were in-line pneumatic screwdrivers measuring 21.6 cm long, 2.5 cm in diameter, weight 450 gm. and are push-to-start, torque controlled tools designed to start when the bit or socket is depressed and stop when this pressure is removed. A clutch mechanism causes the rotor to slip when a screw is tightened to the set torque. The torque is in the 0.9 nm range and the tool was operated at 620 kpa air pressure.

Like most air powered screwdrivers, these are supplied with bare metal handles. Consequently, many workers cover their handles with adhesive tape in an attempt to make the handles more comfortable. Most of the workers on the line wear light cotton gloves with the fingers removed. Many also cover their fingers with tape.

Figure 1 illustrates a representative work station. Hand and waist posture is not a problem since workers operate the in-line tools on a horizontal surface at elbow height while seated at a workbench,[14] where the bench height is 97 cm from the floor.

Partially assembled units are carried on a moving conveyor in a cradle which serves as a fixture for the work piece. A tray located between the operator and the conveyor runs along the entire length of the bench. The tray, from which workers obtain screws to load their screwdrivers, has a perforated bottom. Screws put into the tray are scattered until they are oriented so that the screw head faces upright and the screw shafts are in the holes. A screw is loaded into the screwdriver by positioning the screwdriver bit and socket over the screw head and exerting some pressure. The socket shaft is spring loaded and screws are picked up by the head, so that they are aligned in the proper position to insert into a threaded hole.

Some screwdrivers were attached by the air hose to overhead spring tool balancers. Most of the tools though, were attached to the overhead air supply by the air hose without balancers and held continuously in the operator's hand.

Methods

Two experiments were performed to assess the vibration exposure hazard. The first was an in-plant study to estimate the quantity of vibration exposure for each worker. The daily eight hour exposure was predicted from observed vibration samples for each position on the assembly line. The second experiment was a laboratory study to assess the quality of vibration exposure. Typical tool vibration levels were analysed using a one-third octave band acceleration spectrum of the vibration produced by the tool. Data from these in-plant and laboratory studies were compared with the ISO provisional vibration exposure guidelines to assess the severity of exposure.

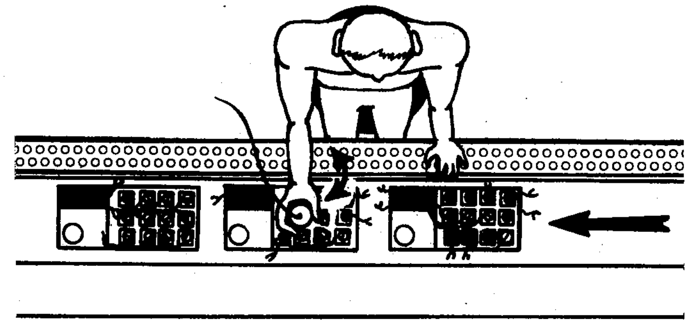

Figure 1 — Representation of a typical workstation. Workers seated around a conveyor load their screwdrivers with screws scattered along a tray with a perforated bottom situated along side of the workbench. The loaded screwdriver is moved into position over a threaded hole with one hand while a wire with a crimped lug is positioned under the screw head with the other hand and the screw installed.

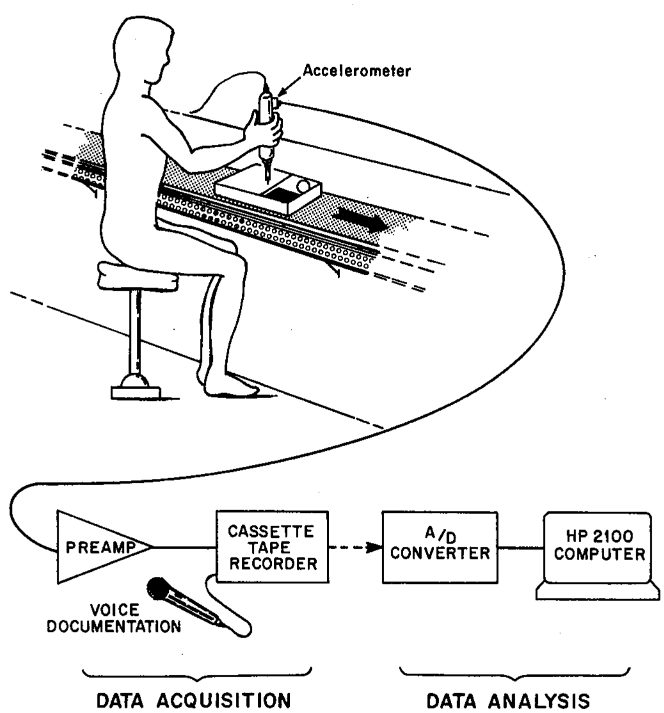

Figure 2 — Instrumentation used in the plant to measure and analyze worker exposure to vibration produced by operation of pneumatic screwdrivers. An accelerometer was attached to each worker's tool and acceleration measurements were recorded for an observation period between five and 20 minutes. Vibration exposure analysis was performed later off-line, in the laboratory.

Measurements conducted at the plant consisted of an appraisal of worker exposure to vibration using recordings from accelerometers which were attached to the tools of each worker operating a pneumatic screwdriver. A Bolt, Beranek and Newman model 506 miniature accelerometer was mounted on a 13 cm × 13 cm × 18 cm plexiglass block which was contoured with a radius and attached to each air screwdriver's handle with a plastic cable tie. The direction of the accelerometer sensitivity was tangential to the screwdriver's circumference. The accelerometer output sensitivity of 10 mV/g was amplified and then recorded using a JVC model KD-1638 two channel portable cassette tape recorder. The second channel was used for voice documentation. The experimental set-up is shown in Figure 2. Vibration measurements from each tool were made for an observation period ranging between 4-18 minutes.

The acceleration recordings made at the plant were analyzed at a later time in the laboratory using a Hewlett Packard 2100 minicomputer and by playing the recorded data into a 10 bit analog-to-digital converter at a sample rate of one msec/sample. The data was filtered using an Ithaco model 4211 band pass filter set between 40 Hz and 315 Hz. The acceleration data was viewed on a Tektronix 4010 graphics CRT screen and artifacts documented on the voice channel during the measurement period such as shock caused by putting the tool on the workbench, moving the tool aside or nudging against the tool while working at another activity were separated from the analysis by an observer. The analysis consisted of measuring the average operation time of the air screwdriver used by each worker. Vibration amplitude and frequency measurements were made at a later time in the laboratory.

There were two phases associated with the screwdriver operation cycle. The first, or "run phase," corresponds to running the screwdriver during screw pick-up and driving a screw. The second, "clutch phase," corresponds to slippage of the screwdriver clutch mechanism when the screw has been tightened to the set torque. The running and clutch slipping phases are illustrated in the acceleration waveform in Figure 3. Visual inspection of the waveform clearly reveals that the vibration produced during the clutch phase is much greater in amplitude and fundamentally lower in frequency than that found during the run phase. The computer was programmed to identify the "run phase" and "clutch phase" on the basis of an empirically derived digital moving average filter.[15]

Total exposure for each operator was computed by measuring samples of their screwdriver operation times and multiplying the cumulative time by the number of operations per shift. The observation interval was measured by calibrating the recorder's interval counter to a stop watch. The sampling period was computed using the number read from the interval counter during playback of the data. The number of operations per eight hour shift for each worker was estimated using the number of operations performed in the observation period.

In the laboratory, a Bruel & Kjaer type 4340 triaxial piezoelectric accelerometer having a charge sensitivity of 20 pC/g was attached to a small aluminum block with a contoured radius using a screw lug. The accelerometer-block assembly was then mounted on a representative screwdriver using an epoxy adhesive. Foam rubber was taped over the accelerometer to prevent changes in temperature caused by cold exhaust air from affecting the measurements. The accelerometer output was coupled to a Kaig Swiss type 5001 charge amplifier and filtered through a low pass filter with a cut-off frequency of 5 KHz.

One third octave band acceleration spectra were measured for vibration in three coordinate axes, x, y, and z. A Nicolet model 444A FFT computing spectrum analyzer, which can produce one-third octave band spectra for continuous input signals, was used. To obtain continous vibration data, the screwdrivers were positioned over a screw that was inserted into an aluminum block with a hole having a slightly larger diameter than its shaft. Thus permitting the screw to turn freely. The spectra were averaged for 10 consecutive 80 msec samples. To measure the one-third octave band spectra for the vibration produced when the screwdriver rotor was locked and the clutch mechanism was slipping, the screwdriver was positioned over an already tightened screw.

Spectra were produced for the clutch screwdriver used on the assembly line studied as well as two other automatic shut-off types which suspend operation of the screwdriver when a screw is tightened.

Results

The average running and clutch slippage time (summarized in Table I) was computed for each worker whose position

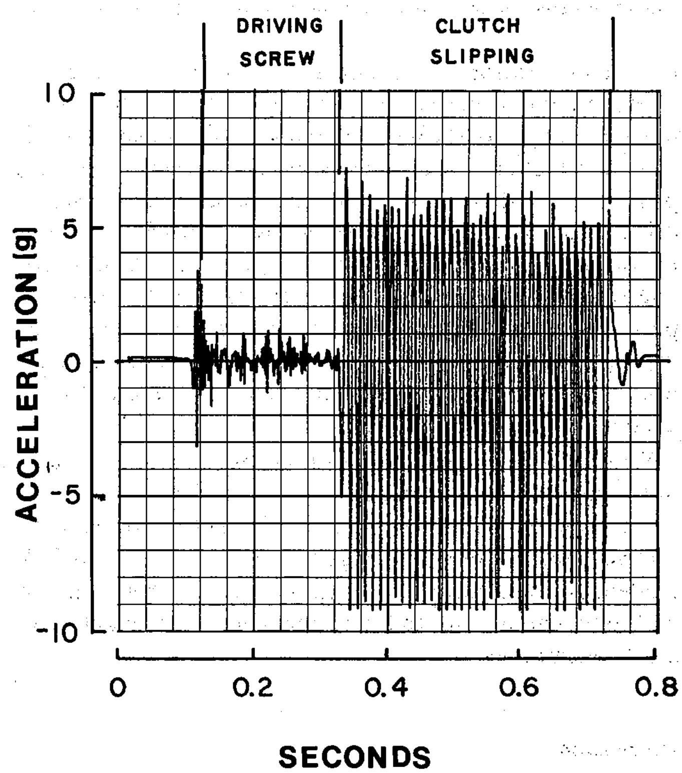

Figure 3 — Representation of a screwdriver vibration acceleration waveform. The vibration produced by the pneumatic screwdriver was categorized into two operation phases: (1) running during screw pickup and driving and (2) clutch slippage.

TABLE I
Mean and Eight Hour Vibration Exposure During Run and Clutch Cycles for Positions Requiring Operation of Power Screwdrivers

Position	No. of Screws/ Cycle	Observation Time (minutes)	Run Cycle: No. of Observations	Run Cycle: Mean Exposure ± S.D. (milliseconds)	Clutch Cycle: No. of Observations	Clutch Cycle: Mean Exposure ± S.D. (milliseconds)	Total 8 Hr Exposure: Run Cycle (minutes)	Total 8 Hr Exposure: Clutch Cycle (minutes)
1	2	6.2	54	123 ± 62	24	89 ± 54	8.6	2.7
2	2	17.1	50	217 ± 95	25	99 ± 29	5.1	1.2
3	2	17.7	102	233 ± 59	49	135 ± 51	10.7	3.0
4	8	5.8	95	259 ± 64	44	161 ± 64	34.0	9.8
5	---[A]	12.6	240	246 ± 32	118	137 ± 46	37.5	10.3
6	5	12.5	251	193 ± 44	123	81 ± 48	31.1	6.3
7	7	13.9	248	204 ± 53	100	66 ± 25	29.1	3.8
8	10	9.9	336	149 ± 45	151	118 ± 51	40.4	14.4
9	10	7.7	261	190 ± 44	113	57 ± 19	51.8	6.7
10	4	17.3	215	194 ± 37	104	162 ± 72	19.3	7.8
11	2	11.7	135	158 ± 31	66	167 ± 59	14.5	7.5
12	3	15.9	104	190 ± 58	50	213 ± 61	10.3	5.4
13	4	13.0	123	179 ± 36	60	102 ± 30	13.6	7.8
14[B]	4	12.3	82	170 ± 23	39	120 ± 35	9.1	3.1
14[C]	1	4.6	32	258 ± 80	28	44 ± 47	14.4	2.1
15	2	12.3	89	180 ± 102	32	164 ± 64	10.5	3.4
16	---	9.8	23	137 ± 77	21	122 ± 74	2.6	2.1
17	2	3.5	16	234 ± 55	16	82 ± 35	8.6	3.0
Average				195		118	19.5	5.6

[A]Variable number of screws per cycle.
[B]Operator uses 2.5 cm screwdriver for this portion of the cycle.
[C]Operator uses 3.4 cm screwdriver for this portion of the cycle.

required operation of a pneumatic screwdriver on the line. The number of observations varied from 16 to 336, depending upon the job of the individual operator. The screwdriver run time included engagement of the screwdriver during pick-up, screwdriver operation and operation of the screwdriver when screws were defective, which usually required operation of the screwdriver in reverse to remove the defective screw. Sometimes several attempts were necessary to pick-up a screw. Slippage of the clutch resulted when a screw was tightened to the required torque. The average total eight hour exposure time was estimated by extrapolating the average run and clutch time.

One-third octave band recordings for the x, y, and z axes in the run and clutch slipping phases for the clutch screwdriver and in the run phases for the automatic shut-off screwdrivers are shown in Figures 4-6. The ISO/DIS 5349 guidelines' daily occupational exposure zones between one-half to two hours, two to four hours and four to eight hours are superimposed.

Discussion

The time that the screwdrivers operate in the run and clutch phases are dependent on several individual operator factors. Operators load their screwdrivers by pressing the tool over a screw which usually activates the push-to-start pneumatic motor. In the event that a screw is cross-threaded, operators often take advantage of the action of the clutch slipping to prevent from falling behind and use the screwdriver as an impact wrench to force the screw into place rather than replace the defective screw. Additionally, if co-workers do fall behind they may be helped by a worker in their neighboring station, since they work for a group incentive. The vibration exposure for any operator is thus very difficult to estimate from the number of screws assigned to an individual task and the production rate alone.

The total eight hour exposure to vibration for workers on the line during the running portion of the screwdriver operation cycle ranged between 2.6 minutes and 51.8 minutes (See Table I). The total eight hour exposure to vibration produced during clutch slippage ranged between 1.2 minutes and 14.4 minutes. The exposure times measured in this investigation were conservative since the production rate for the line on the day that these measurements were made was 0.3 units per minute lower than on a typical day.

Six of the 17 positions, positions 4, 5, 6, 7, 8 and 9 (See Table I) approached or exceeded 30 minutes of total exposure to vibration produced during running. These jobs involved installation of the greatest number of screws on the line. Additionally, although the job of position 14B involved the installation of only one screw, the mean exposure time during the run cycle was 258 msec. This was because position 14B

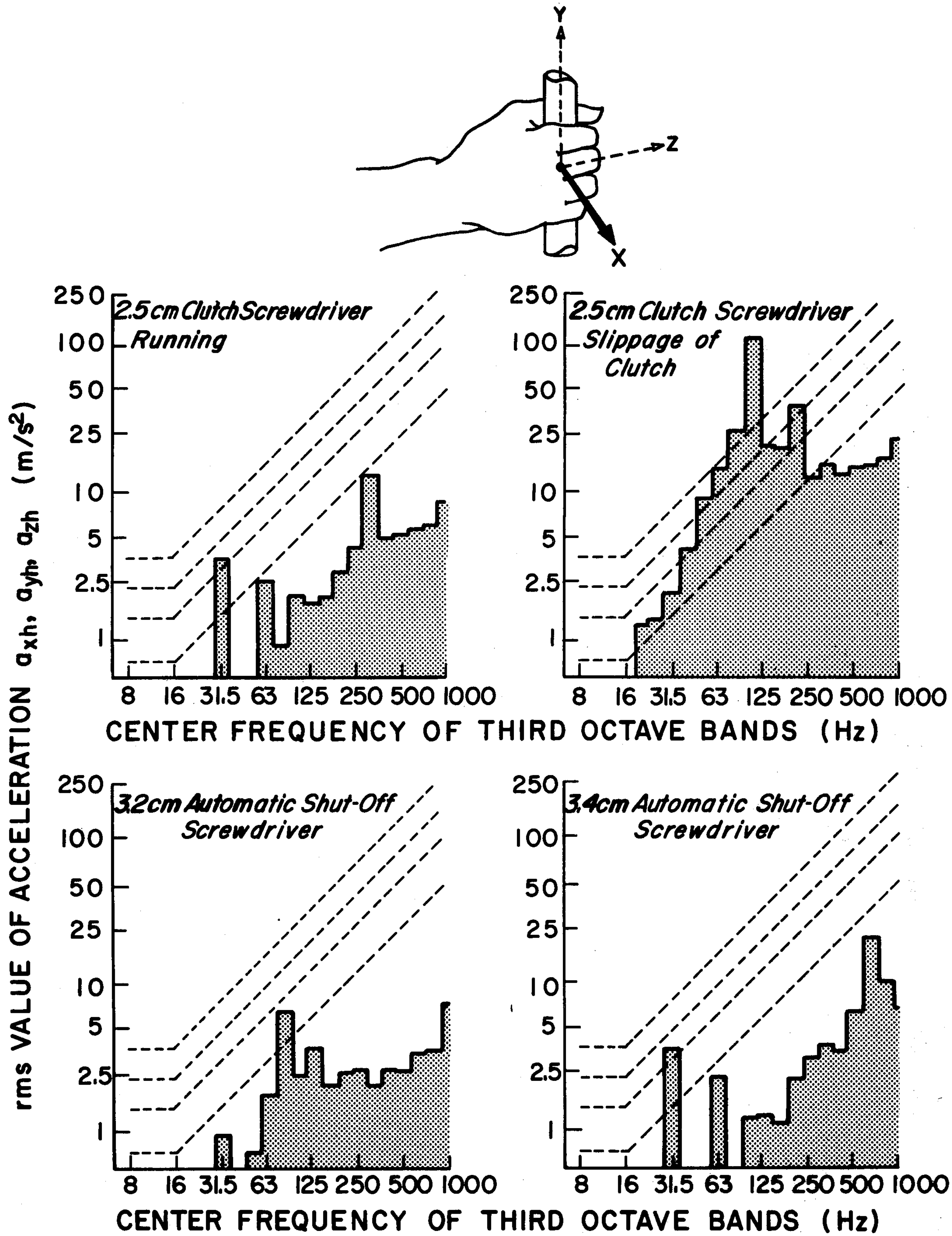

Figure 4 — X-axis one-third octave band spectra for the 2.5 cm diameter clutch screwdriver running, slippage of the clutch, 3.2 cm diameter automatic shut-off screwdriver and 3.4 cm diameter automatic shut-off screwdriver running. The ISO exposure provisional hand and arm vibration exposure guideline boundaries are superimposed.[13]

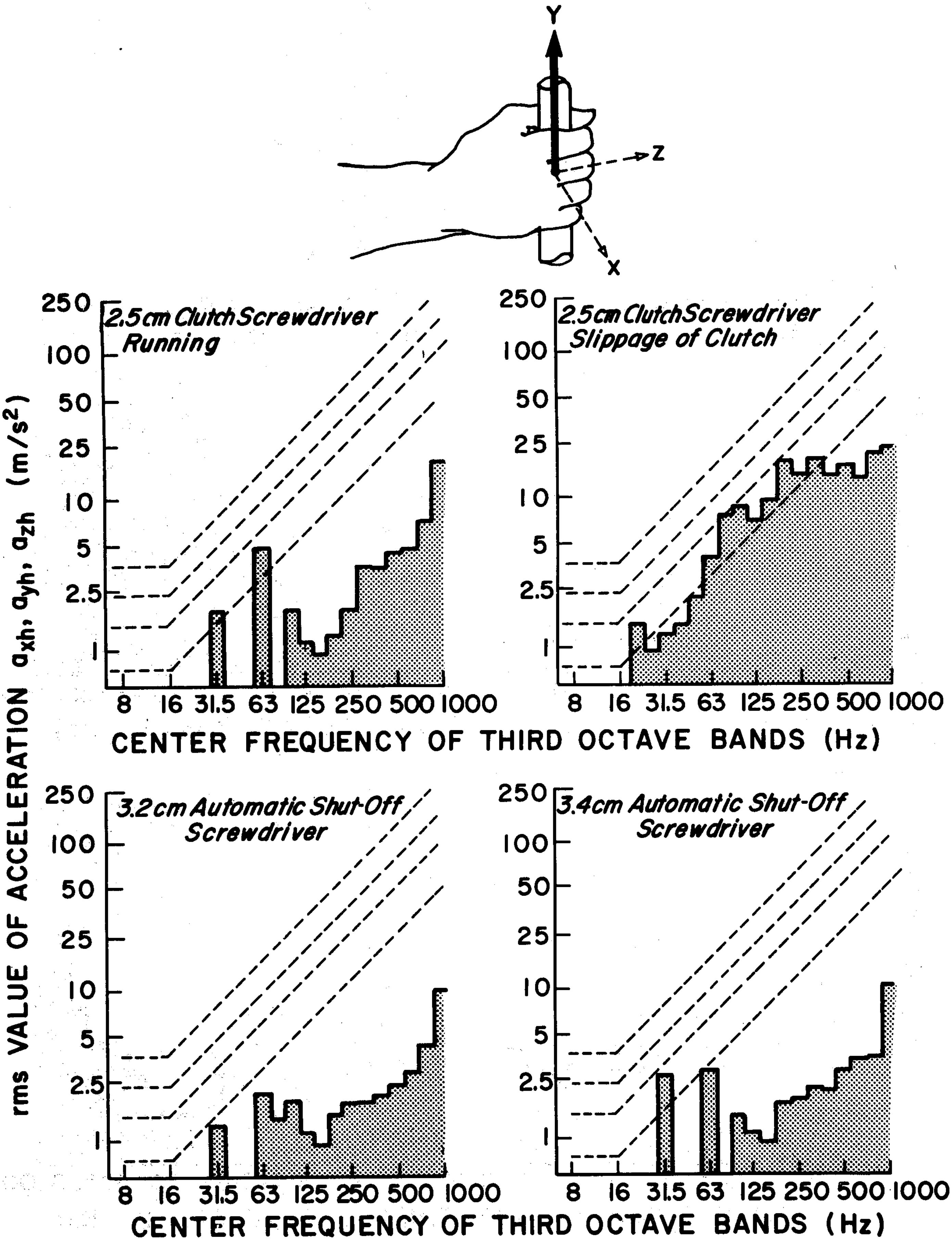

Figure 5 — Y-axis one-third octave band spectra for the 2.5 cm diameter clutch screwdriver running, slippage of the clutch, 3.2 cm diameter automatic shut-off screwdriver and 3.4 cm diameter automatic shut-off screwdriver running. The ISO exposure provisional hand and arm vibration exposure guideline boundaries are superimposed.[13]

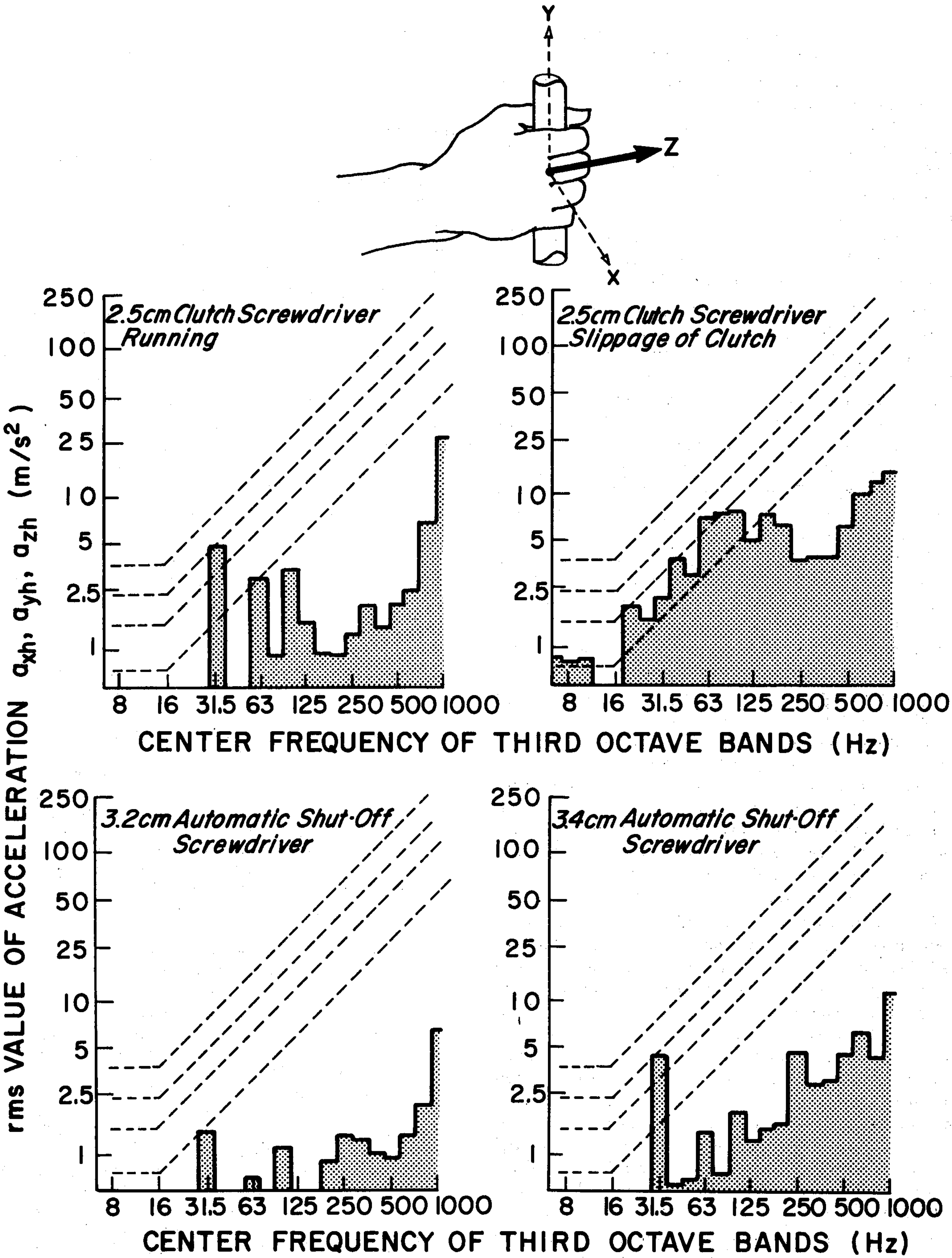

Figure 6 — Z-axis one-third octave band spectra for the 2.5 cm diameter clutch screwdriver running, slippage of the clutch, 3.2 cm diameter automatic shut-off screwdriver and 3.4 cm diameter automatic shut-off screwdriver running. The ISO exposure provisional hand and arm vibration exposure guideline boundaries are superimposed.[13]

required the installation of a screw that was longer than the others, which explaines the high running time measurement.

The one-third octave band spectra for the screwdrivers measured in the x, y, and z axes during continuous running were within the ISO proposed two to four hour exposure boundaries (See Figures 4-6). The greatest one-third octave band frequency component was at 31.5 Hz. The maximum predicted eight-hour exposure for the workers observed during the run phase was less than one hour. Consequently, all of the workers observed were subject to vibration within the ISO guidelines for vibrations produced during the run phase of the screwdriver operation cycle.

One-third octave band spectra during the clutch slippage phase exceeded the 1/2 to two hour exposure boundaries in the x-axis (tangential) by about 12 dB in band 20 (center frequency 100 Hz). See Figure 4. However, one-third octave band vibration acceleration spectra measured in the y and z axes during clutch slippage were within the ISO proposed two to four hour exposure boundaries. See Figures 5-6. The average eight hour exposure time during the clutch slippage phase for the workers observed was 5.6 minutes.

Variations in the plant exposure times are primarily due to the number of screws installed per cycle, the type of screw installed and individual worker differences in operating the screwdrivers. Some workers tend to run the screwdriver longer when picking up screws and let the rotor locking clutch slip for a longer time than others. Other sources of variation include individual tool differences such as type, age and maintenence histories.

One control measure is rebalancing the line to minimize vibration exposure by reducing the number of screws installed and redistribute the designated screws for some positions. Another remedy to this situation is the installation of pneumatic screwdrivers which feature automatic shut-off when the tool reaches a set torque, which eliminates clutch slippage. The one-third octave band spectra measurements for two such screwdrivers are shown in Figures 4-6. The vibration levels produced were below the ISO proposed exposure boundaries for the exposure times observed.

The ISO provisional hand transmitted vibration exposure boundaries are tentative maximum exposure guidelines for daily exposure. They represent the best guidance available for acceptable levels but do not necessarily represent the limits of safe exposure. Therefore the vibration associated with air screwdrivers as a factor of repetitive trauma disorders cannot be ruled out because the screwdrivers tested were within the ISO guidelines. In fact the results showed that there was significant vibration exposure associated with these tools. Alternative screwdrivers should be tested so that those which minimize transmission of vibration to the hand and minimize worker force exertions can be selected for repetitive jobs — especially in those situations where repetitive trauma disorders have been reported.

Accurate estimation of worker vibration exposure is necessary when comparing alternative tool vibration signatures and using the ISO guidelines as a bench mark. Since hand tool operation is subject to a high degree of variability in many types of assembly operations, the need to implement vibration exposure measurements by directly sampling is indicated to accurately estimate vibration exposure.

Summary

This work demonstrates that assessment of daily worker vibration exposure in a bench assembly operation can be made by sampling directly the vibration produced from the tools of individual operators. Still, vibration exposure is difficult to predict due to variable operating techniques between workers and working conditions between jobs. Studies were performed on small in-line hand-held pneumatic screwdrivers in the 0.9 nm torque range. Exposure data collected in the plant were used in conjunction with laboratory measurements of typical tool one-third octave band acceleration spectra to compare worker exposure with the ISO exposure guidelines for hand-transmitted vibration. They showed that even in jobs where these screwdrivers were operated for no more than an average of 300 msec per cycle, exposures were in excess of available guidelines. Recommendations for vibration control included selecting tools that use air shut-off rather than clutches to control torques, rebalancing the line to reduce the number of screws installed in some positions and redistributing the type of screws assigned to some positions to minimize vibration exposure.

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