Grip Pressure Distribution Under Static and Dynamic Loading

by R. Gurram, G.J. Gouw and S. Rakheja

ABSTRACT—The dynamic response of a vibrating hand-arm system is strongly related to the grip force. While the relationship between total grip force and vibration characteristics of the hand-arm system has been extensively studied, no attempts have been made to investigate the distribution of grip pressure at the hand-handle interface. The local grip-pressure distribution may be more closely related to the finger blood flow, fatigue and loss of productivity than total grip force. In the present study, distribution of static and dynamic forces at a hand-handle interface is investigated using a grid of pressure sensors mounted on the handle. The pressure distribution is acquired for different values of static and dynamic grip forces in the range of 25-150 N. The dynamic measurements were conducted at various discrete frequencies in the 20-1000 Hz range with peak acceleration levels of 0.5 g, 1.0 g, 2.0 g and 3.0 g. The grip-pressure distribution under static loads revealed a concentration of high pressures near the tips of the index and middle fingers, and the base of the thumb. This concentration of high pressures shifted towards the middle of the fingers under dynamic loads, irrespective of grip force, excitation frequency and acceleration levels. These local pressure peaks may be related to impairment of blood flow to finger tips and the possible causation of vibration white finger.

Introduction

High levels of vibrations transmitted to operators of hand-held power tools and off-road vehicles have been related to various occupational health disorders, fatigue and loss of productivity. Several investigators have established that prolonged exposure to such vibrations can cause vibration white finger (VWF) disease associated with impaired blood flow among hand-tool operators, and severe spinal and stomach disorders among vehicle drivers.[1-3] The transmitted vibration levels, invariably measured using accelerometers, have been assessed in an attempt to identify the mechanisms related to VWF or spinal disorders. The transmitted hand-arm vibrations are measured either at the handle or at the operator's wrist[4,5] while the driver vibrations are acquired at the driver-seat interface using the three-axis seat accelerometer.[6] Although a measure of overall transmitted vibrations can be attained, such acceleration measurements do not provide the distribution of dynamic forces at the human-machine interface. The distribution of forces at the human-machine interface under static and dynamic loading can provide considerable insight into the transmission of localized forces and stresses experienced by operators. In the case of hand-held power tools, the grip-pressure distribution (GPD) under dynamic conditions can be used to investigate hand injury and fatigue mechanisms, and to carry out design and ergonomic evaluation of handle grips.[7] The pressure distribution at the driver-seat interface can provide objective data to study the spine loads, and to design effective seat cushions and back-rests with load distributing capabilities. The measurement of pressure distribution at the human-machine interface, however, is highly complex due to associated curved surfaces and flexibility of interface. In this paper two different types of flexible pressure sensors are investigated to acquire the pressure distribution at a hand-handle interface under static and dynamic conditions. The GPD measured at the hand-handle interface was analyzed to illustrate the influence of grip-force and handle-vibration characteristics on the occurrence of high localized dynamic pressures at the operator's hand.

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Interface Pressure Sensors

Measurement of the pressure distribution at a human-machine interface requires a comprehensive grid of thin and flexible sensors, such that the viscoelastic properties of the interface remain unaltered during static and dynamic measurements. In the recent past, a number of interface pressure measuring systems have been developed. Sensors such as rubber butterfly valves, manometers, sprung flat boards, strain gages, silicon diaphragms and foil capacitors have been used in conjunction with multi-channel data-acquisition systems to acquire the distribution of pressure at the human-seat interface.[8,9] All these sensors pose severe limitations in view of the flexibility of the interface. These sensors either are applicable to hard surfaces or alter the elastic properties of the human-seat interface. The pressure distribution at the hand-tool interface has been acquired using a pressure resistive paint,[10] conductive thioplastic sensors,[11] and force-sensing resistors[7] to achieve an accurate measurement of static grip forces.

Piché *et al.*[12] used force sensing resistors to study the static pressures at a human seat interface. The basic sensing element was an ultra thin and flexible force sensing resistor, and a film of foil conductors. The force-sensing resistor consisted of a polymer sheet with a layer of flexible sensing film. The foil-conductor film was a Mylar sheet with a pattern of open-ended conductors. The infinite resistance of open-ended conductors was shunted by placing the force-sensitive resistor against the foil film. The resistance changed with changes in the applied load. The shunt resistance of the assembly was thus related to the force applied to the surface. The 9.75-mm diameter sensing assembly, comprised of two polymer sheets, was 0.25-mm thick.

In this study, the flexible resistive and capacitive sensors, which offer the potential to acquire static as well as dynamic pressures, were investigated to acquire the GPD at the hand-handle interface. A resistive pressure sensing grid was first fabricated, where each sensor is supplied with a 0.24-mA constant current at 1.5 V. A conditioning circuit was integrated and the sensors were calibrated to determine the force-resistance relationship, and the precision and repeatability using a pneumatic actuator. The static calibration curve, shown in Fig. 1, exhibited nonlinear characteristics with large hysteresis. Although the sensors showed good repeatability over a short period, the repeatability and dynamic range deteriorated quite rapidly due to oxidation of the foil conductors. These sensors were thus considered infeasible for the present study.

Alternatively, a pressure-measurement system using flexible variable capacitance sensors, a conditioning circuit and data-acquisition software, referred to as EMED system (developed by NOVEL gmbh, Beichstrabe 8, 8000 Munich 40, Germany), was employed to acquire the GPD. EMED is an electronic measurement system for recording and evaluating pressure distribution on flat and curved surfaces.[13] The EMED sensor consisted of a pressure-sensing element sandwiched by an elastic synthetic mat. A schematic of a variable-capacitance pressure-sensing element is illustrated in Fig. 2.

The measurement system provided digital voltage (AD) values proportional to the variations in sensor capacitance with the applied load. The sensors, designed for a maximum pressure of 400 kPa, were excited with 20-V peak-peak voltage at 200 kHz. Each sensor was calibrated by applying known pressures using a pneumatic actuator. The schematic of the sensor calibrating setup is shown in Fig. 3. The sensor signals were then digitized to obtain the corresponding AD values. Figure 4 illustrates a typical nonlinear calibration curve of the capacitive sensor in the

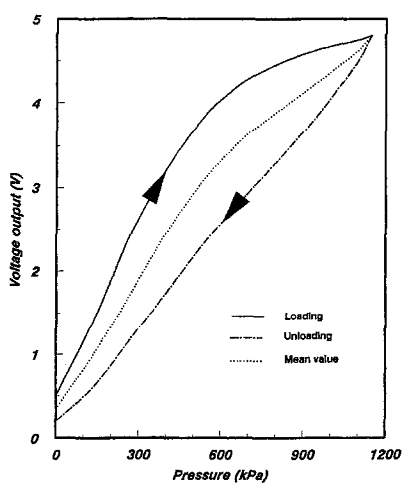
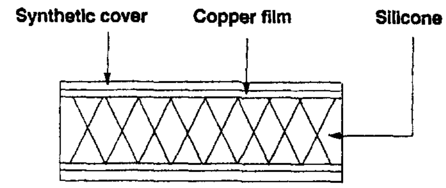
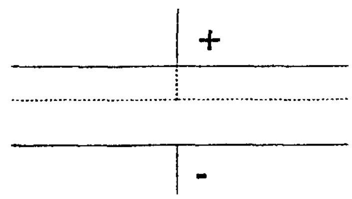


Fig. 1—Calibration curve of a resistive pressure sensor



(a) Schematic of a variable capacitance sensor



(b) Equivalent electrical circuit of pressure sensor

Fig. 2—Schematic of an EMED capacitive sensor and its equivalent electrical circuit

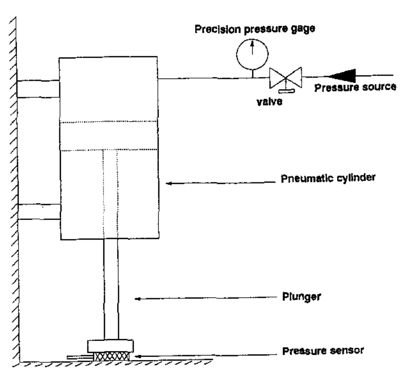


Fig. 3—Schematic of the sensor calibration setup

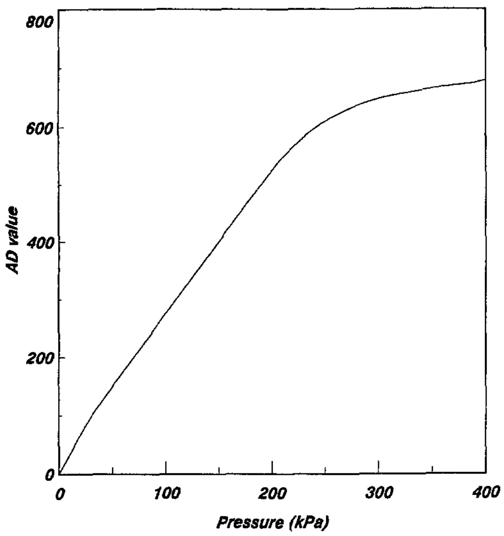


Fig. 4—Calibration curve of an EMED capacitive pressure sensor

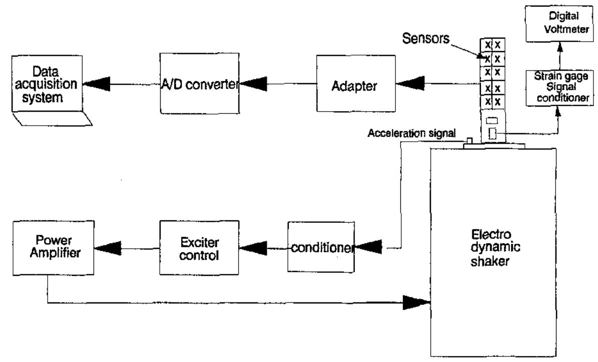


Fig. 5—Schematic of the grip-pressure measurement system

pressure range of 0-400 kPa. The calibration curve, approximated by a third-order polynomial, reveals that pressures in excess of 250-kPa yield poor resolution of the sensor.

A grid of 20 sensors was fabricated to acquire the local pressure distribution at the hand-handle interface. The instantaneous AD value, the time and the coordinates of each sensor were recorded using the EMED data acquisition software. The data acquisition and EMED system allowed both static and dynamic measurements with a maximum speed of 150,000 samples/s.

Measurement of Grip-pressure Distribution

A 38-mm diameter, I-shaped handle was instrumented with a matrix of 20 flexible variable capacitance EMED pressure sensors to measure the GPD under various loading conditions. The instrumented handle was mounted on an electrodynamic vibration exciter such that either harmonic or random vibrations may be generated along its longitudinal axis. The handle was split along its axial-direction axis and strain gages were used to measure the total grip force exerted by the subjects.[14, 15] In view of the symmetric nature of the grip force on either side of the split handle only two strain gages were mounted in a half-bridge configuration. One gage was mounted in the axial direction to measure the bending strain caused by the grip force, while the second gage was oriented perpendicular to the first gage for temperature compensation.[14, 15] The strain gages were calibrated using Vishay Electronics strain gage conditioner, by applying known loads at a preselected location along the axial axis of the handle. The subjects were advised to grip the handle around the preselected location. The total grip force measured by the strain gages was displayed to the subject through a digital voltmeter to enable the subject to maintain nearly constant grip force. Figure 5 illustrates the schematic of the measurement system.

Two subjects were used to acquire the GPD under static and dynamic loading conditions. Each subject was advised to maintain an identical posture during all the experiments and to grip the handle with the dominant right hand while keeping the forearm horizontal with an elbow angle of 90 deg. The subjects were advised to maintain constant total grip force by monitoring the strain-gage signal displayed on the digital voltmeter. The gripping hand of each subject was positioned on the handle in a specific manner to attain a predetermined sensor pattern as shown in Fig. 6.

The static and dynamic GPD were acquired for grip forces of 25 N, 50 N, 100 N and 150 N. The dynamic GPD was obtained under harmonic excitations of constant peak accelerations of 0.5 g, 1.0 g, 2.0 g and 3.0 g at discrete frequencies of 20 Hz, 30 Hz, 100 Hz, 200 Hz, 500 Hz and 1000 Hz. The static GPD measurements at 50-N grip force were performed four times and the data were examined for repeatability. Similarly, the repeatability of dynamic GPD was examined by measuring GPD for 50-N grip force and 2.0-g peak acceleration at 100 Hz. The experiments showed good repeatability.

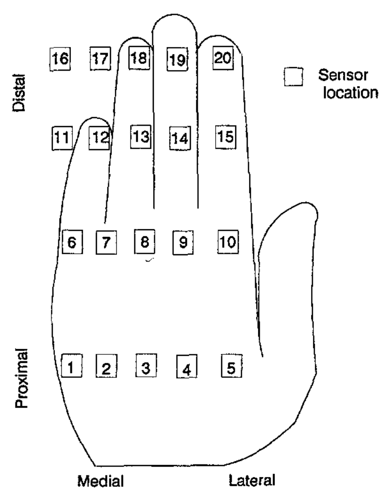


Fig. 6—Location of pressure sensors on a stretched hand

Results and Discussion

The measured data were averaged and analyzed for different static and dynamic test conditions to highlight the influence of grip force, and characteristics of handle vibration on the local concentration of forces at the hand-handle interface. The measurements performed on the selected subjects revealed a high degree of consistency in terms of the location of the peak pressures. The detailed results are thus discussed in terms of the data obtained from a single subject. Since it is not feasible to report all the data obtained during the tests, only a representative set of data is discussed in this section. The unreported results, however, revealed similar pattern of GPD under varying dynamic conditions.

Figure 7 presents the GPD under 50-N grip force for static and dynamic (2.0-g peak acceleration at 20 Hz) testing conditions, as a function of the longitudinal and lateral coordinates of the hand. The sensor location on the hand is described in terms of its coordinates with reference to the approximate midpoint of the base of the hand. The location of sensors is described as distal and proximal along the longitudinal axis, and as lateral and medial along the lateral axis. The figure reveals a high concentration of pressure at the index finger tip (sensor# 20) under static loads. The pressure at the base of the thumb (sensor# 4, 5, 10) and tip of the middle finger (sensor# 19) are also observed to be high. While the magnitude of peak pressure varies significantly with the level of grip force, the peak pressure occurs at the tip of the index finger (sensor# 20), irrespective of the magnitude of the grip force. Under dynamic loads, the GPD data reveal a concentration of high pressures on the lateral section of the hand, while the medial section is exposed to considerably lower levels of local pressures. A comparison of the GPD data reveals that pressure peaks at the tips of index and middle fingers under static load (sensors# 20, 19) tend to shift towards the middle of fingers under dynamic grip force (sensors# 10, 14, 15). The magnitude of the pressure peak at the index finger tip, measured under static load decreases considerably under dynamic load, while the magnitude of the local pressure at middle increases.

Figure 8 illustrates the GPD acquired for a grip force of 100 N under static and dynamic testing conditions. The dynamic measurements are performed for 1.0-g peak acceleration at 100 Hz. A comparison of Figs. 7 and 8 demonstrates similar pattern of GPD under static as well as dynamic loading. While the magnitude of peak pressure increases considerably with an increase in the static grip force, the location of the peak pressure remains unchanged, as illustrated in Table 1. The peak pressure under dynamic loading also increases considerably with the grip force, as shown in Table 2. The change in magnitude of the peak pressure, however, is relatively insignificant with variations in excitation frequency and acceleration. The location of peak pressure is observed to be near the middle of the index finger irrespective of the dynamic loading conditions.

Various studies have established that tips of the index, middle and ring fingers are the first parts of the hand affected by the VWF disease.[16,17] The occurrence of excessive pressure at the middle of these fingers can greatly reduce the blood supply to their tips. This factor, together with several other factors, such as prolonged exposure to vibration, may be related to causation of VWF among hand-held power tool operators.

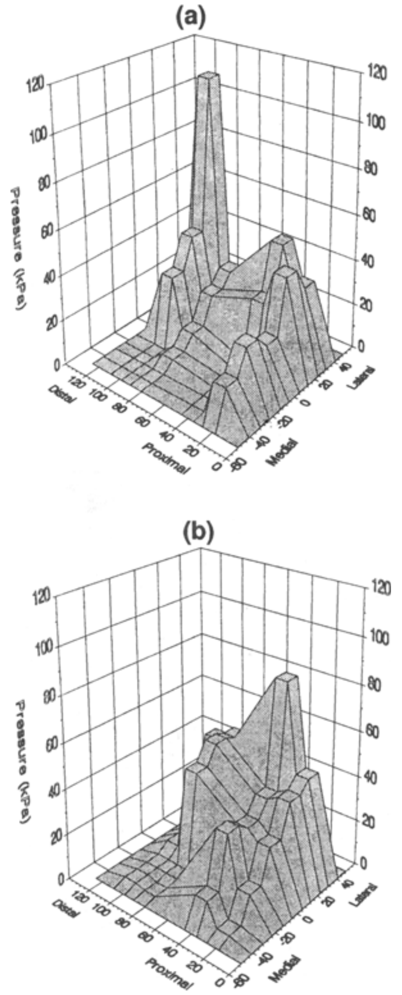


Fig. 7—Grip-pressure distribution under a 50-N grip force: (a) Static; (b) 2.0-g peak acceleration at 20 Hz

Conclusions

The GPD at the hand-handle interface was measured under static and dynamic loading to study the influence of the magnitude of grip force, and the vibration characteristics on the local pressures at the interface. The flexible resistive sensors were found to be inadequate due to their hysteresis and poor repeatability of results. Variable capacitance pressure sensors were used to obtain the GPD at various loading conditions. The dynamic tests were performed for 25-N, 50-N, 100-N and 150-N grip forces at 0.5-g, 1.0-g, 2.0-g and 3.0-g peak acceleration levels in the frequency range of 20-1000 Hz. The results of the study revealed a high concentration of pressure at the tips of the index and middle fingers, and the base of the thumb under static grip forces. These pressure peaks shifted towards the

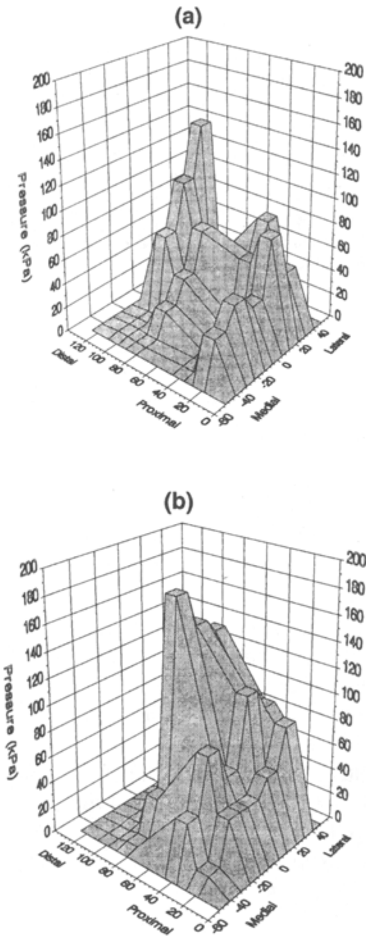


Fig. 8—Grip-pressure distribution under a 100-N grip force: (a) Static; (b) 1.0-g peak acceleration at 100 Hz

middle of the fingers under application of dynamic loads, irrespective of magnitude of the grip force, vibration frequency and acceleration level. A high concentration of pressure at middle of the fingers can cause reduced blood flow to the finger tips. This impairment of blood flow may contribute to the causation of vibration white finger upon prolonged exposure to vibration.

TABLE 1—LOCATION OF PEAK PRESSURES (STATIC LOADING)

Grip Force (N)	Peak Pressure (kPa)	Sensor Location
25	66	Tip of the index finger
50	110	
100	145	

TABLE 2—LOCATION OF PEAK PRESSURES (DYNAMIC LOADING)

Grip Force (N)	Peak Acceleratio n	Frequency (Hz)	Peak Pressure (kPa)	Sensor Location
25	1.0 g	200	67	Middle of the index finger
50	2.0 g	50	92	
100	3.0 g	1000	225	

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References

1. Wassermann, D.E., Human Aspects of Occupational Vibration, Elsevier Science Pub., 7-34 (1987).

2. Brammer, A.J., Relations Between Vibration Exposure and the Development of the Vibration Syndrome, ed. Brammer and Taylor, Vibration Effects on the Hand and Arm in Industry, John Wiley & Sons, New York, 283-290 (1982).

3. Gruber, G.J., "Relationship Between Whole-body Vibration and Morbidity Patterns among Interstate Truck Drivers," NIOSH Publication No. 77-167 (1976).

4. Wasserman, D.E., Reynolds, D.D., Behrens, V., Samueloff, S. and Basel, R., "Vibration White Finger Disease in U.S. Workers Using Pneumatic Chipping and Grinding Hand-Tools," Vol. II, Engineering Testing, NIOSH Publication No. 82-101 (1982).

5. Pyykkö, I., Färkkilä, M., Toivanen, J., Korhonen, O. and Hyvärinen, J., "Transmission of Vibration in the Hand-Arm System with Special Reference to Changes in Compression Force and Acceleration," Scandinavian J. Work, Environment and Health, **2**, *87-95 (1976).*

6. Rasmussen, G., "Human Body Vibration Exposure and Its Measurements," Bruel and Kjaer Tech. Rev. No. 1, (1982).

7. Fellows, G.L. and Frievalds, A., "Ergonomics Evaluation of a Foam Rubber Grip for Tool Handles," Appl. Ergonomics, 225-230 (1991).

8. Linden, O., Greenway, R.M. and Piazza, J.M., "Pressure Distribution on the Surface of the Human Body: I. Evaluation in Lying and Sitting Positions Using a Bed of Springs and Nails," Arch. of Phys. Med. & Rehab., 378-385 (1965).

9. Holly, L.K., "A New Pressure Measuring System for Cushions and Beds with a Review of the Literature," Paraplegia, **17**, *461-474 (1979).*

10. Abrams, C.F., "Modeling the Vibrational Characteristics of the Human Hand by Driving Point Mechanical Impedance Method," North Carolina State Univ. Raleigh, PhD Thesis (unpublished), 28-29 (1971).

11. Krause, P., Orban A., Panzke, K.J. and Popov, K., "Critical Assessment of Common Methods to Determine Vibrational Stress of Hand-arm System," Int. Symp. Man Under Vibration Suffering and Protection, Udine (Italy), 261-274 (1979).

12. Piché, A., Rakheja, S., Gouw, G.J. and Sankar, T.S., "Development of an Elastic Human-seat Interface Pressure Sensing System," ICAART 88, Montreal, 118-119 (1988).

13. Seitz, P., Personal communications on MICROEMED system developed by NOVEL gmbh, Germany, (1990).

14. Mishoe, J.W. and Suggs, C.W., "Hand-arm Vibration. Part II: Vibrational Responses of the Human Hand," J. Sound and Vib., **53**, *545-558 (1974).*

15. Wood, L.A., Suggs, C.W. and Abrams, C.F., "Hand-arm Vibration Part III: A Distributed Parameter Dynamic Model of the Human Hand-arm System," J. Sound and Vib., **57**, *157-169 (1978).*

16. Brubaker, R.L., Mackenzie, C.J.G. and Bates, D.V., "Vibration White Finger Disease Among Tree Fellers in British Columbia," J. Occupational Medicine, **25**, *403-408 (1983).*

17. Hellström, B. and Andersen, K.L., "Vibration Injuries in Norwegian Forest Workers," Brit. J. Ind. Medicine, **29**, *255-263 (1972).*