Influence of dual vibrations on control of percussive hand-operated power tools – experimental investigations

Abstract
This article presents the results of pioneer experimental research into the impact of whole body vibration (WBV) and hand arm vibration (HAV) with different amplitudes and frequencies on percussive tools which are controlled by hand. In these studies the human operator is considered as the active element of the control system. The quality of control executed by the participants of the tests was assessed by the typical parameters existing in control system engineering, such as rise time, settling time, overshoot and integral square error (ISE). The tests were performed on an especially built stand. Results are presented in the form of time histories of step reference force. Forces realized by the operator were statistically analysed and graphically presented. Local (HAV) vibration of tools and accompanying dynamic forces between the handle and the vibrating tool have a big influence on control of the tool. An increase in the frequency of the tools’ vibration increases the adjustment range. The influence of platform vibrations on the adjustment range is relatively small.

Keywords: Human as manual tool control system, Influence of WBV and HAV on man’s control reactions

Streszczenie
W artykule przedstawiono pionierskie wyniki badań doświadczalnych wpływu wibracji ogólnej i miejscowej o różnej amplitudzie i częstotliwości na sterowanie ręcznym narzędziem wibroduarowym. Człowiek-operator jest tu traktowany jako aktywny element układu sterowania. Jakość sterowania wykonywanego przez uczestników testów jest oceniana poprzez typowe parametry takie jak czas narastania, czas regulacji, przeregulowanie czy wskaźnik ISE. Testy były wykonywane na specjalnie zbudowanym stanowisku. Wyniki są zaprezentowane w formie przebiegów czasowych na skokowy sygnał referencyjny. Siły wywierane przez operatora zostały opracowane statystycznie i przedstawione graficznie. Wibracje miejscowe narzędzi wraz z towarzyszącymi im siłami dynamicznymi mają duży wpływ na sterowanie narzędziem. Wraz ze wzrostem częstotliwości wibracji wzrasta zakres odchyłek od wymaganej siły. Wpływ wibracji platformy na ten zakres jest relatywnie mały.

Słowa kluczowe: człowiek jako element układu sterowania narzędziem, wpływ wibracji ogólnej i miejscowej na sterowanie
1. Introduction

Human-machine interactions are one of the most interesting and difficult branches of science. The reason for this is because of the variety of the human form, physical connections between machine and operator and various other dependencies. All of these factors determine the final results of each measurement, modelling and assessment of man-machine systems. The first significant works concerning the interaction between the pilot and the control system of an aeroplane were provided by [8]. A more general approach was presented in [9]. Some aspects of the influence of whole body vibration upon human-operators’ reactions and comfort were described in [2] and [10]. From the 1960s up until the time of writing this paper, many works and experiments concerning various approaches to human-machine studies have been conducted, predominantly in military laboratories.

The experimental investigations described in this paper are a continuation of a series of experiments carried out by [1, 5] showing the new effects of various factors on the manual control of hand-operated power tools.

![Fig. 1. General flow diagram of signals](image)

In the tests, the human operator is treated as an element of the control-visual feedback regulator. The general scheme of the block diagram of the human–operator feedback control system is shown in Fig. 1.

2. Materials and methods

The experimental studies were conducted on the modified test bench used previously in the works of [3, 4, 7]. In the present paper, a new approach was applied and described for the human-operator subjected simultaneously to two sources of vibrations acting upon legs and hands. A schema of the used test bench with its principal components is shown in Fig. 2.

A photograph of the experimental test bench is presented in Fig. 3. The modified stand was designed as a system composed of a platform, two vertical bars and a horizontal beam placed on the piston of the electro-hydraulic Heckert SHA 140 shaker. Figure 3 shows the vertical and horizontal shakers and corresponding directions of applied excitations. As is shown in Fig. 3, the human-operator stands with one foot forward to the front of the tool on the vibrating platform holding in his hands the handle of the vibrating hand-tool whilst
watching the monitor screen. The task of the operator is to control the motion of the tool by exerting pressure on the handle in accordance with the tracking value displayed on the monitor’s screen. Real-time visualisation of the two signals is realised on the front panel of a virtual instrument within LabView 7.1, shown in Fig. 4, in the form of two mobile, coloured indicators, allowing their comparison. The human-operator tool system is treated here as a typical system of control with visual feedback.
As the input signal is assigned to the monitor (a sudden step force of 80 [N]), the operator must match this value by applying pressure on the handle of the tool. The tool is connected to the other components of the test-bench through the integrated force sensor. The force exerted by the operator is continuously displayed on the monitor screen. It allows, by visual feedback and observation of state error between two signals displaced on the monitor, comparison between applied and reference forces.

Execution of the task by the operator has deliberately been made more difficult by introducing distortions coming from the vibrating platform (WBV-whole body vibration) and the vibrations of the tool (HAV-hand arm vibrations). The design of the measuring test-bench allows the introduction of different frequencies and amplitudes of vibrations submitted to the operator. The Heckert electro-hydraulic shaker vibrates the measuring platform in accordance with instructions from the controlling unit. During the tests, the shakers were controlled by sine functions with frequencies 3, 5, 10 and 15 Hz and the amplitudes corresponding to the data frequency exposure nuisance limit for standard exposures of 15 minutes. The hand tool controlled by the operator was set in oscillatory motion by the horizontal electromagnetic shaker shown in Figures 3 and 4. The frequencies generated by the shaker and the platform were assumed to be the same in order to fortify the effect of the influence of vibration disturbances on the operator.

The following factors have been implemented and realized in the LabView software environment: the generation of input force; the measurement of the input force; the force exerted by the operator; the visualization and registration of both forces. Figure 5 shows the signal flow diagram of the program. The test consists of a strain gauge force sensor in the full bridge dedicated to the sensor amplifier, the strain gauge power supplier, measurement card NI DAQ 6024E together with the connections and measurement computer equipped with LabView software. A measuring track diagram is shown in Fig. 5.
3. Results

The tests were conducted in the laboratory at the Department of Dynamics of Material Systems of Cracow University of Technology for 7 selected volunteers. Each of the participants stood on the measuring platform in a defined position under the following three conditions: 1) control of pressure force on the tool handle without whole body vibration (WBV) but with hand arm vibration (HAV); 2) control of pressure force on the tool handle with whole body vibration (WBV) only; 3) control of the realized pressure force on the tool handle with both whole body vibration (WBV) and hand arm vibration (HAV) acting simultaneously. All of the tests were carried out under the influence of vibrations with sequential frequencies 3, 5, 10, 15 Hz. Each attempt was recorded in the form of time histories of the input sudden step reference forces and the response forces exerted by the operator on the tool handle. The measured signals were sampled with a frequency of 5 kHz. Figures 6–13 show examples of typical time responses registered for different trails.

![Fig. 5. Measuring track diagram](image)

![Fig. 6. The time history of the force realized by the operator subjected only to platform vibration with a frequency of 3 [Hz]](image)
Fig. 7. The time history of the force realized by the operator subjected simultaneously to platform and tool vibration with the same frequency of 3 [Hz]

Fig. 8. The time history of the force realized by the operator only subjected to platform vibration with a frequency of 5 [Hz]

Fig. 9. The time history of the force realized by the operator subjected to platform and tool vibration simultaneously with the same frequency of 5 [Hz]
Fig. 10. The time history of the force realized by the operator subjected only to platform vibration with a frequency of 10 [Hz].

Fig. 11. The time history of the force realized by the operator subjected simultaneously to platform and tool vibration with the same frequency of 10 [Hz].

Fig. 12. The time history of the force realized by the operator only subjected to platform vibration with a frequency of 15 [Hz].
4. Discussion

The timing signals of the input force and the realized force have been processed in the D-plot software (HydeSoft USA). Because of the high gain signals from the bridge failures and performing measurements in a hall in which other used devices were submitted to some excitations (general and local vibrations), the signals from the sensor force had to be pre-filtered to remove the interference of external perturbations. Scaling was then made using earlier measurement calibration. The timeline was moved so that the sudden force stroke began at time 0 [s]. For each time history, two reference lines were generated with values equal to the input step force value of 80 [N] +/–5%. Thus, prepared time responses were used to analyze the quality of tool control by the operator in individual trials. The measures of quality tool control executed by the participants of the test were represented by typical parameters existing in control system engineering such as rise time, settling time, overshoot and integral square error (ISE) based on the difference $e(t)$ between realized $r(t)$ and reference $f(t)$ forces shown in formula (1).

$$e(t) = r(t) - f(t)$$

(1)

The integral square error was calculated according to formula (2). The time of integration for each test was aggregated from $t = 0$ to $t_k = 4.5$ [sec].

$$ISE = \int_0^{t_k} e^2(t) dt$$

(2)

Figure 15 shows an example of a time history of a realized force with the related ISE index in time domain from 0 to 4.5 [sec], equal to the area of the field presented in grey.

These parameters were calculated and presented on the basis of all registered time responses. During the analysis of the test results of conditions with distortion in the form of local vibration tools, a problem appeared relating to the settling time evaluation. It happened that some operators repeatedly failed to find the exerted force within the defined a priori
channel limited by the two reference lines ±5% of the reference force value. Another measure of quality control used during the analysis was the ISE performance index. The ISE was calculated for the chosen a priori, fixed settling time durations. Both the value of the possible ranges of adjustment in individual trials, as well as the value of ISE, were tabulated. Drawn-up scoreboards were used for statistical calculations in which the medians and ranges of considered values of parameters were assessed. The results of the experiments were presented in the form of bar charts showing the median and ranges of the results for individual trials in Figures 15–17.

Fig. 14. Example of time history of realized force with the related ISE index

Fig. 15. Medians and ranges of rise time for subsequent tests

Rise time is an indicator, which gives information about the time in which the considered system managed to achieve an adjustable value in the range of 0.1 to 0.9 of its final value. In the case of the human-tool system, it also includes information about the human response time and on the nature of this reaction, e.g. whether it is fast and violent or slow. Distortions in the form of ground shakes and tool shakes can influence and affect the human-operator’s reaction causing lack of concentration and difficulties in controlling the tools. The above
charts indicate a longer response time and a greater dispersion of results for lower frequency vibration platforms and tools. A large dispersion of the results and a long rise time especially apply to tests for vibration of the platform itself - that is, the effect of the whole body vibration with a frequency of $5 \text{ [Hz]}$. These results are consistent with indicated standard curves [6], where a frequency of $5 \text{ [Hz]}$ is particularly troublesome for the human being.

![Fig. 16. Possible control range for subsequent tests](image)

A typical indicator of control quality adjustment can be the time within which the test begins to set the size to a layout of $+/-5\%$ and keeps the value within this range. Unfortunately, in the described studies of the human-tool system, reaching the desired value in the required range was unsuccessful in many cases. Therefore, the assessment of all the attempts by a single

![Fig. 17. Values of ISE index for subsequent tests](image)
criterion, such as time regulation, was not possible. Instead, another assessment of operator action was proposed by the statistical charts representing the extent to which the operator tried to place exerted force into the required range.

The index ISE allows for aggregating errors during each trial and comparison of all attempts made. The same time (4.5 [sec]) was assumed for the comparison of all tests. Figure 17 presents the corresponding results.

5. Conclusions

The human-operator as the control element in human-machine systems, which is presented in this paper, largely affects the dynamic characteristics of the system as a whole. The graphs show that the biggest impact here is had by local (HAV) vibration of tools and accompanying dynamic forces between the handle and the vibrating tool. An increase in the frequency of the tools’ vibration increases the adjustment range. The influence of platform vibrations on the adjustment range is relatively small. Typical for dynamic systems without human interaction parameters, such as settling time, rise time or overshoot, are fundamentally different from those of the human-machine parameters in terms of both quality and quantity that can be noted in Figs 5–13. This is the result of the inherent mental features of the individual operator. As a result of this, each dynamic layout containing the human must be assessed as the system with parameters stochastically variable with time and described by using stochastic differential equations. However, this is related to many mathematical and experimental difficulties concerning the probability distributions of parameters of the system, and therefore, scientific works with this approach have been relatively over-looked in previous literature.

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