Safety of heavy-duty dump trucks in operation

B L Gerike¹², V I Klishin¹, Yu V Drozdenko² and P B Gerike¹

¹Federal Research Center of Coal and Coal Chemistry, Siberian Branch, Russian Academy of Sciences, 10 Leningradskiy ave., Kemerovo, 650065, Russia
²Gorbachev Kuzbass State Technical University, 28 Vesennyaya str., Kemerovo, 650000, Russia

E-mail: am_besten@mail.ru

Abstract. One of the health risks of drivers operating large dump trucks inside open pit mines is exposure to excess whole-body and local vibration, which results in high intensity of work (class 3.3). It is proposed to find sources of excess vibrations by vibro diagnostics in parking tests of dump trucks as influence of external factors (haul profiles, road gradients, etc.) are eliminated in this case. The spectrum of vibrations allows determination of a defect type at high reliability (probability p≥0.9).

1. Introduction
The frequent occupational decease of dump truck operators is connected with excess local and whole-body vibration in the operator control area [1–3]. This problem can be solved through reduction in the length of the working shift of drivers. However, this requirement is often impossible to fulfill in the present-day open pit mines due to the specificity of work organization. Despite progressive improvement in design and maintenance of big dump trucks, it brings no decrease in the rate of the work-related decease of heavy-duty dump truck operators [4, 5].

One of the most reasonable approaches to finding and identifying various dynamic faults in manufacture, assembly and operation of mining machines, including large dump trucks, is vibration diagnostics [6–9]. It allows detection and testing of incipient defects at the reliability of 90% [8, 10–13].

2. Testing procedure
Vibration diagnostics belongs to the performance-based methods of state estimation of equipment [9, 11]. Thus, it is applicable to dump trucks when in motion, or during loading and unloading. On the other hand, it is more expedient to carry out the diagnostic study of dump trucks and to detect defective equipment when the dump trucks are in the parking position, at different power settings (idling, rated engine rpm, full speed rpm allowed in parking tests) and with simultaneous sequential power-off of attached implements (hydraulic pumps, drive shaft and fan impeller).

The diagnostic test characters are vibration velocity \( V \), vibration accelerations \( a \) and vibration displacements \( S \) measured in the frequency band [3, 4000 Hz].

Table 1 presents the comparative appraisal of working conditions with thresholds and allowable levels of the vibration acceleration.
**Table 1.** European versus Russian classes of working conditions.

| European Vibration Directive 2002/44/EC (whole-body vibration) [14] | Russian classification of working conditions (total and local vibration) [15–17] |
|---|---|
| Unacceptable level $a > 1.15$ m/s$^2$ | 4 | $a_z > 8.9$ m/s$^2$; $a_{x,y} > 6.3$ m/s$^2$ | Extreme |
| Red | 3.4 | $a_z = 4.46$–8.9 m/s$^2$; $a_{x,y} = 3.2$–6.3 m/s$^2$ |
| | 3.3 | $a_z = 2.23$–4.46 m/s$^2$; $a_{x,y} = 1.6$–3.2 m/s$^2$ |
| | 3.2 | $a_z = 1.12$–2.23 m/s$^2$; $a_{x,y} = 0.79$–1.6 m/s$^2$ | Harmful |
| Threshold $a = 1.15$ m/s$^2$ | Yellow | 3.1 | $a_z = 0.56$–1.12 m/s$^2$; $a_{x,y} = 0.4$–0.79 m/s$^2$ |
| | Green | 2 | $a_z < 0.56$ m/s$^2$; $a_{x,y} < 0.4$ m/s$^2$ | Allowable |
| Allowable level $a \leq 1.15$ m/s$^2$ | | | $a_z = 0$ m/s$^2$; $a_{x,y} = 0$ m/s$^2$ | Optimal |

Figure 1 shows the check points of local vibration measurements in driver cab. The sources of excess vibration were found in vibro tests of units that generated vibrations (diesel engine and generator).

Figure 2 shows the measurement check points of local vibration on the left side of diesel engine. The same pattern of vibration measurements was used for the right side of the engine.

Figure 3 presents the check points of local vibration measurement for generator.

For assessing measurement error, three measurements were taken at each check point, which provided confidence probability of 90%.

![Figure 1. Map of vibration measurement on driver seat, cab floor and steering wheel.](image1)

![Figure 2. Vibration measurement points on diesel engine (left side).](image2)

![Figure 3. Vibration measurement points on generator.](image3)
3. Measurement results

The test object was dump truck BelAZ-75306, property of the Vinogradovsky open pit mine, Kuzbass Fuel Company. During operation, the dump truck operator felt excess vibration. As per the selected procedure, the vibro-tests were implemented in the parking position, with sequential power-off of attached implements. From the analysis of vibrations affecting the operator (table 2), the vibration acceleration grows to maximum on the cab floor (whole-body vibration) in vertical direction at idle speed: \(a_{\text{max}} = 0.77 \text{ m/s}^2\), which exceeds the maximum allowable value \(a = 0.5 \text{ m/s}^2\) \([14–17]\). As follows from the spectral analysis of the vibration accelerations (figure 4), vibration insulation of the cab let the mechanical vibrations generated by the engine pass to the cab floor.

The analysis of vibration affecting the driver shows that the peak value of the vibration acceleration on hands-arms on the steering wheel (local vibration) reaches \(a_{\text{max}} = 0.40 \text{ m/s}^2\) at idle speed, which exceeds the maximum permissible value \(a = 2.5 \text{ m/s}^2\) \([14–17]\).

The spectral analysis of vibrations measured on the steering wheel points at unsatisfactory work of the engine (figure 5). The second and higher harmonics appear, as well as a harmonic arises at the half frequency of the crankshaft speed. These are the evidence of improper performance of the engine power system.

According to the analysis of the parking test results, the main source of mechanical vibrations is the diesel engine of the dump truck (table 3). However, the maximum vibration acceleration \(a_{\text{max}} \approx 27 \text{ m/s}^2\), which is lower than the maximum allowable value \(a = 4g\), while the vibration velocity \(V = 6.2 < \|V\| = 7.2 \text{ mm/s}\), which implies that the diesel engine is in the satisfactory technical state.

The increase in the engine speed from 800 rpm (idling) to 1200 rpm (maximum rotational speed in the parking tests) always results in the decrease in the vibration intensity \(V_{\text{SKZ}}\) though the vibration acceleration always grows in value in this case. Power-off of the attached implements (pump, drive shaft and fan impeller) has nearly no influence on the total and local vibrations while the pattern of the vibration process somewhat (slightly) alters.

![Figure 4. Vertical vibration of the cab floor, \(n=800\) rpm and \(a=0.77\) m/s².](image)

![Figure 5. Spectrum of vibrations on steering wheel: (a) vertical vibrations \((n=800\) min\(^{-1}\); \(a=0.36\) m/s²); (b) transverse vibration \((n=800\) min\(^{-1}\); \(a=0.38\) m/s²); (c) transverse vibration \((n=1000\) min\(^{-1}\); \(a=0.31\) m/s².](image)
Table 2. Vibrations felt by truck operator.

| Description          | Fully assembled Engine rpm speed, min⁻¹ |
|----------------------|----------------------------------------|
|                      | 800  | 1000  | 1200  |
| **Driver chair**     |      |       |       |
| vertical vibration  | V=1.76 mm/s; | V=0.55 mm/s; | V=0.85 mm/s; |
| α=0.29 m/s²;        | α=0.24 m/s²; | α=0.37 m/s²; |       |
| S=75 μm             | S=15 μm | S=21 μm |       |
| **Driver chair**     |      |       |       |
| transverse vibration| V=1.39 mm/s; | V=0.42 mm/s; | V=1.17 mm/s; |
| α=0.17 m/s²;        | α=0.14 m/s²; | α=0.35 m/s²; |       |
| S=68 μm             | S=18 μm | S=19 μm |       |
| **Steering wheel**  |      |       |       |
| vertical vibration  | V=2.96 mm/s; | V=0.93 mm/s; | V=1.17 mm/s; |
| α=0.36 m/s²;        | α=0.19 m/s²; | α=0.20 m/s²; |       |
| S=99 μm             | S=17 μm | S=30 μm |       |
| **Steering wheel**  |      |       |       |
| transverse vibration| V=2.81 mm/s; | V=1.26 mm/s; | V=1.01 mm/s; |
| α=0.38 m/s²;        | α=0.31 m/s²; | α=0.22 m/s²; |       |
| S=120 μm            | S=41 μm | S=20 μm |       |
| **Driver cab**      |      |       |       |
| vertical vibration  | V=7.19 mm/s; | V=0.50 mm/s; | V=2.38 mm/s; |
| α=0.77 m/s²;        | α=0.18 m/s²; | α=0.20 m/s²; |       |
| S=222 μm            | S=17 μm | S=26 μm |       |
| **Driver cab**      |      |       |       |
| transverse vibration| V=4.03 mm/s; | V=1.13 mm/s; | V=0.73 mm/s; |
| α=0.44 m/s²;        | α=0.24 m/s²; | α=0.22 m/s²; |       |
| S=183 μm            | S=29 μm | S=25 μm |       |

Continuation of table 2.

| Description          | Pump and drive shaft cut-off Engine rpm speed, min⁻¹ |
|----------------------|---------------------------------------------|
|                      | 800  | 1000  | 1200  |
| **Driver chair**     |      |       |       |
| vertical vibration  | V=1.18 mm/s; | V=0.59 mm/s; | V=0.54 mm/s; |
| α=0.22 m/s²;        | α=0.24 m/s²; | α=0.35 m/s²; |       |
| S=43 μm             | S=19 μm | S=13 μm |       |
| **Driver chair**     |      |       |       |
| transverse vibration| V=0.97 mm/s; | V=0.56 mm/s; | V=0.55 mm/s; |
| α=0.15 m/s²;        | α=0.14 m/s²; | α=0.22 m/s²; |       |
| S=41 μm             | S=16 μm | S=9 μm |       |
| **Steering wheel**  |      |       |       |
| vertical vibration  | V=2.68 mm/s; | V=1.13 mm/s; | V=1.18 mm/s; |
| α=0.31 m/s²;        | α=0.22 m/s²; | α=0.15 m/s²; |       |
| S=89 μm             | S=16 μm | S=15 μm |       |
| **Steering wheel**  |      |       |       |
| transverse vibration| V=2.10 mm/s; | V=0.99 mm/s; | V=0.72 mm/s; |
| α=0.30 m/s²;        | α=0.29 m/s²; | α=0.25 m/s²; |       |
| S=83 μm             | S=33 μm | S=13 μm |       |
| **Driver cab**      |      |       |       |
| vertical vibration  | V=1.88 mm/s; | V=1.08 mm/s; | V=0.80 mm/s; |
| α=0.25 m/s²;        | α=0.32 m/s²; | α=0.20 m/s²; |       |
| S=72 μm             | S=23 μm | S=12 μm |       |
| **Driver cab**      |      |       |       |
| transverse vibration| V=3.48 mm/s; | V=1.19 mm/s; | V=0.68 mm/s; |
| α=0.41 m/s²;        | α=0.15 m/s²; | α=0.20 m/s²; |       |
| S=130 μm            | S=45 μm | S=18 μm |       |

Continuation of table 2.

| Description          | Fan impeller, pump and drive shaft cut-off Engine rpm speed, min⁻¹ |
|----------------------|---------------------------------------------|
|                      | 800  | 1000  | 1200  |
| **Driver chair**     |      |       |       |
| vertical vibration  | V=1.18 mm/s; | V=0.92 mm/s; | V=0.52 mm/s; |
| α=0.23 m/s²;        | α=0.29 m/s²; | α=0.43 m/s²; |       |
| S=32 μm             | S=20 μm | S=8 μm |       |
| **Driver chair**     |      |       |       |
| vertical vibration  | V=1.44 mm/s; | V=0.55 mm/s; | V=0.93 mm/s; |
transverse vibration $a=0.19$ m/s$^2$; $a=0.13$ m/s$^2$; $a=0.28$ m/s$^2$; $S=49$ μm $S=19$ μm $S=14$ μm
Steering wheel, vertical vibration $a=0.31$ m/s$^2$; $a=0.26$ m/s$^2$; $a=0.14$ m/s$^2$; $S=83$ μm $S=15$ μm $S=10$ μm
Steering wheel, transverse vibration $a=0.34$ m/s$^2$; $a=0.18$ m/s$^2$; $a=0.40$ m/s$^2$; $S=50$ μm $S=39$ μm $S=19$ μm
Driver cab, vertical vibration $a=0.23$ m/s$^2$; $a=0.19$ m/s$^2$; $a=0.19$ m/s$^2$; $S=57$ μm $S=27$ μm $S=10$ μm
Driver cab, transverse vibration $a=0.61$ m/s$^2$; $a=0.18$ m/s$^2$; $a=0.18$ m/s$^2$; $S=118$ μm $S=64$ μm $S=21$ μm

Table 3. Vibration generated by engine installation of dump truck.

| Description          | Fully assembled | Engine rpm speed, min$^{-1}$ |
|----------------------|-----------------|-----------------------------|
|                      | 800             | 1000                        | 1200                        |
| Engine base          | $V=1.79$ mm/s;  | $V=1.84$ mm/s; $V=3.56$ mm/s; |
| left side,           | $a=3.37$ m/s$^2$; | $a=3.62$ m/s$^2$; $a=5.40$ m/s$^2$; |
| vertical             | $S=56$ μm       | $S=50$ μm                   | $S=102$ μm                  |
| Engine base          | $V=3.67$ mm/s;  | $V=2.97$ mm/s; $V=6.23$ mm/s; |
| left side,           | $a=3.01$ m/s$^2$; | $a=3.26$ m/s$^2$; $a=5.21$ m/s$^2$; |
| transverse           | $S=160$ μm      | $S=146$ μm                  | $S=174$ μm                  |
| Engine base          | $V=2.10$ mm/s;  | $V=2.22$ mm/s; $V=3.49$ mm/s; |
| right side,          | $a=3.63$ m/s$^2$; | $a=4.64$ m/s$^2$; $a=5.910$ m/s$^2$; |
| vertical             | $S=51$ μm       | $S=43$ μm                   | $S=64$ μm                   |
| Engine base          | $V=3.48$ mm/s;  | $V=2.88$ mm/s; $V=6.22$ mm/s; |
| right side,          | $a=3.26$ m/s$^2$; | $a=3.96$ m/s$^2$; $a=5.90$ m/s$^2$; |
| transverse           | $S=146$ μm      | $S=100$ μm                  | $S=153$ μm                  |
| Cylinder barrel      | $V=2.26$ mm/s;  | $V=2.30$ mm/s; $V=3.58$ mm/s; |
| left side,           | $a=17.09$ m/s$^2$; | $a=19.16$ m/s$^2$; $a=23.68$ m/s$^2$; |
| vertical             | $S=119$ μm      | $S=81$ μm                   | $S=133$ μm                  |
| Cylinder barrel      | $V=1.42$ mm/s;  | $V=1.46$ mm/s; $V=2.87$ mm/s; |
| left side,           | $a=20.01$ m/s$^2$; | $a=23.71$ m/s$^2$; $a=26.68$ m/s$^2$; |
| transverse           | $S=25$ μm       | $S=28$ μm                   | $S=51$ μm                   |
| Engine flange        | $V=1.87$ mm/s;  | $V=1.88$ mm/s; $V=2.39$ mm/s; |
| center,              | $a=12.00$ m/s$^2$; | $a=12.57$ m/s$^2$; $a=19.46$ m/s$^2$; |
| vertical             | $S=43$ μm       | $S=42$ μm                   | $S=47$ μm                   |
| Engine flange        | $V=1.53$ mm/s;  | $V=1.59$ mm/s; $V=2.40$ mm/s; |
| center,              | $a=16.91$ m/s$^2$; | $a=18.80$ m/s$^2$; $a=27.22$ m/s$^2$; |
| transverse           | $S=22$ μm       | $S=22$ μm                   | $S=29$ μm                   |

Continuation of table 3.

| Description          | Pump and drive shaft cut-off | Engine rpm speed, min$^{-1}$ |
|----------------------|------------------------------|-----------------------------|
|                      | 800             | 1000                        | 1200                        |
| Engine base          | $V=1.91$ mm/s;  | $V=1.82$ mm/s; $V=3.75$ mm/s; |
| left side,           | $a=3.83$ m/s$^2$; | $a=3.83$ m/s$^2$; $a=6.36$ m/s$^2$; |
| vertical             | $S=36$ μm       | $S=36$ μm                   | $S=98$ μm                   |
| Engine base          | $V=3.02$ mm/s;  | $V=2.84$ mm/s; $V=6.42$ mm/s; |
| left side,           | $a=3.23$ m/s$^2$; | $a=3.23$ m/s$^2$; $a=5.36$ m/s$^2$; |
| transverse           | $S=115$ μm      | $S=115$ μm                  | $S=150$ μm                  |
In summary, we can state that:

- It is only possible to find the excess vibration sources using the performance-based method, namely, vibro diagnostics;
- The only way to find faults of manufacture, assembly and operation of heavy-duty dump trucks is the parking tests as they eliminate external effects exerted on the vibration process by such factors as gradients of roads and profile irregularity heights.

### 4. Conclusions

| Description                  | Fan impeller, pump and drive shaft cut-off | Engine rpm speed, min⁻¹ |
|------------------------------|-------------------------------------------|--------------------------|
|                              | Engine base                               | 800                      | 1000                      | 1200                      |
|                              | V=2.52 mm/s; a=8.15 m/s²; S=79 μm          | V=2.09 mm/s; a=3.07 m/s²; S=45 μm | V=4.62 mm/s; a=5.98 m/s²; S=105 μm |
|                              |                                           | 800                      | 1000                      | 1200                      |
|                              | Engine base                               | V=3.43 mm/s; a=19.22 m/s²; S=36 μm      | V=2.67 mm/s; a=3.35 m/s²; S=73 μm | V=6.66 mm/s; a=4.47 m/s²; S=52 μm |
| left side,                   |                                           | 800                      | 1000                      | 1200                      |
| vertical                     |                                           | V=2.18 mm/s; a=3.90 m/s²; S=38 μm      | V=2.22 mm/s; a=4.98 m/s²; S=34 μm | V=3.65 mm/s; a=6.22 m/s²; S=56 μm |
| Engine base                  |                                           | 800                      | 1000                      | 1200                      |
| left side,                   |                                           | V=3.56 mm/s; a=3.51 m/s²; S=71 μm      | V=2.73 mm/s; a=4.22 m/s²; S=60 μm | V=6.17 mm/s; a=5.56 m/s²; S=136 μm |
| right side,                  |                                           | 800                      | 1000                      | 1200                      |
| vertical                     |                                           | V=1.50 mm/s; a=6.45 m/s²; S=39 μm      | V=1.82 mm/s; a=9.84 m/s²; S=34 μm | V=3.65 mm/s; a=6.22 m/s²; S=56 μm |
| Cylinder barrel              |                                           | 800                      | 1000                      | 1200                      |
| left side,                   |                                           | V=1.29 mm/s; a=16.50 m/s²; S=32 μm      | V=1.61 mm/s; a=23.63 m/s²; S=36 μm | V=6.17 mm/s; a=5.56 m/s²; S=136 μm |
| vertical                     |                                           | 800                      | 1000                      | 1200                      |
| Cylinder barrel              |                                           | V=2.66 mm/s; a=8.14 m/s²; S=79 μm      | V=2.02 mm/s; a=4.80 m/s²; S=54 μm | V=2.45 mm/s; a=15.10 m/s²; S=52 μm |
| left side,                   |                                           | 800                      | 1000                      | 1200                      |
| Engine flange center,        |                                           | V=1.92 mm/s; a=19.22 m/s²; S=36 μm      | V=2.34 mm/s; a=10.51 m/s²; S=49 μm | V=2.81 mm/s; a=28.51 m/s²; S=25 μm |
| vertical                     |                                           | 800                      | 1000                      | 1200                      |
| Engine flange center,        |                                           | V=1.92 mm/s; a=19.22 m/s²; S=36 μm      | V=2.34 mm/s; a=10.51 m/s²; S=49 μm | V=2.81 mm/s; a=28.51 m/s²; S=25 μm |
| transverse                   |                                           | 800                      | 1000                      | 1200                      |
The spectral analysis of vibration allows highly reliable (probability $p \geq 0.9$) identification of defects and, using the Russian classification of working conditions, definition of the revealed defect hazard.

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