Improved seat reduces jarring/jolting for operators of low-coal shuttle cars

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Abstract

The prolonged exposure of equipment operators to shock and whole-body vibration (WBV) is linked to cumulative back, neck and abdominal disorders. In low coal mines, space restrictions make it difficult for seat suspensions to isolate operators from shock and WBV. Researchers at NIOSH's Pittsburgh Research Laboratory are responding to these issues by investigating viscoelastic foams. For the full-load case, an ergonomic seat made with viscoelastic foams can isolate the shuttle-car operator from shock at 15 Hz. Researchers used results from additional foam testing using an analytical model to identify viscoelastic foams that provide shock isolation at a frequency below 5 Hz.

Introduction

Nearly one-third of the equipment operators in underground coal mines experience adverse levels of exposure to whole-body vibration (WBV) (Remington et al., 1984). Shuttle cars are major sources of WBV exposure, with operators being exposed to WBV and shock when the shuttle car travels over rough mine floors characterized by numerous bumps, ruts and potholes. In low coal mines, seat suspension systems are difficult to design because of space restrictions. The seriousness of prolonged exposure to WBV and shock is demonstrated by their connection to cumulative back, neck and abdominal disorders. For underground-equipment operators in New South Wales, Australia, the number of back injuries caused by vehicle jarring is equal to the number of back injuries caused by overexertion (Cross and Walters, 1991).

Morever, a review of the shuttle-car injuries recorded in the Mine Safety and Health Administration's (MSHA's) database for 1997 is revealing. Of the injuries pertaining to the back, neck and head, 57 of 100 resulted directly from the jarring of the seated operator while driving the vehicle. This number translates to 25% of the total shuttle-car injuries in 1997 that were related to jolting/jarring of the operator.

With input from underground shuttle-car operators, this study addressed a component of WBV that is germane to underground mining — high-energy impacts or shocks. Shuttle-car operators complained largely about the jolting and jarring they experienced when traveling over rough bottom. Thus, the research focused on a means for better isolating the shuttle-car operator from the jolts and jars caused largely by the high-level, low-frequency, terrain-induced impacts. The approach was to develop an improved seat that incorporated more ergonomic design features and that would use viscoelastic foam padding as the principal way of isolating the shuttle car operator from shock impacts.

Field data collection

At a drift mine in eastern Kentucky, National Institute for Occupational Safety and Health (NIOSH) researchers recorded data on the original seat of a JOY 21SC shuttle car (Fig. 1) and on a redesigned version of the seat (Fig. 2). The coal seam at the mine has a thickness of 0.89 m (35 in.) and an operating height of approximately 1.1 m (43 in.). These conditions require shuttle-car operators to assume a reclining posture when traveling in their vehicles. The original seat provided little lower-back support and adjustability. Considering the shortcomings of the original seat, NIOSH researchers modified it to include the following ergonomic features:

- An easily adjustable lumbar support.
- Fore-aft seat pan movement.
- Seat padding composed of viscoelastic foam.

Seat padding included six 12.7-mm (0.5-in.) layers of the following configuration from top to bottom: Extra-Soft, Pudgee, Blue, Yellow, Soft and Green (Fig. 3). The Blue, Yellow and Green layers are Confor medium-density, open-celled polyurethane foams from E-A-R Specialty Composites Corp., Newark, DE. The Extra-Soft and Soft are Sun-Mate polyurethane foams with an organic composition of more than 50% plant derivatives. Sun-Mate Pudgee is a viscoelastic gel-foam with a unique composition and soft doughlike consistency.

Data were recorded along a typical stretch of roadway with the

FIGURE 1

Original seat.

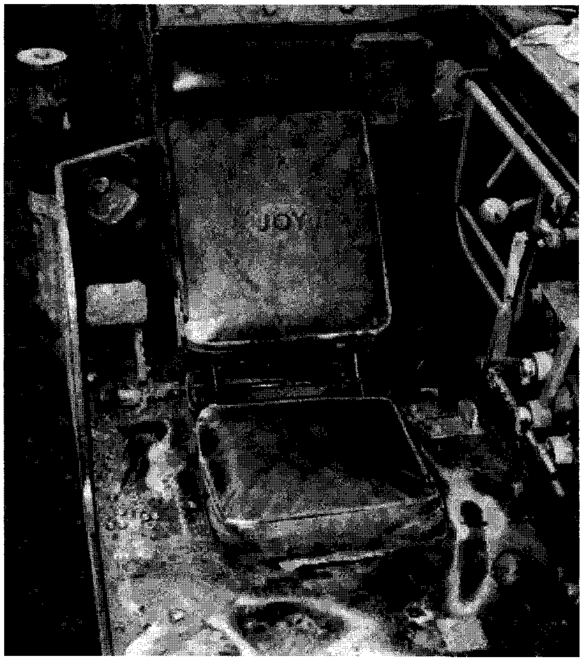
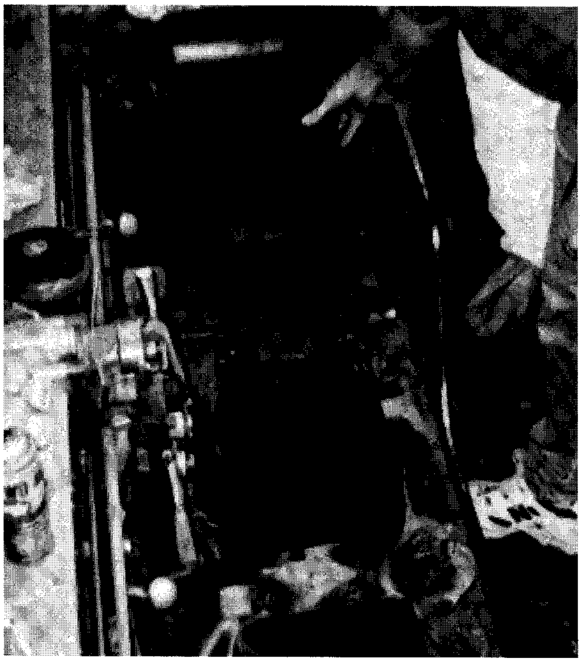


FIGURE 2

Ergonomic seat.



shuttle-car operating empty and operating with a full load. The resulting data analysis showed improved isolation for the ergonomic seat in the full load case. Isolation was achieved at 15 Hz.

Although this configuration of viscoelastic foams provided significantly improved isolation for the shuttle-car operator, NIOSH researchers were interested in further reducing the isolation frequency, considering the effects of shock and WBV on the human body, as shown in Fig. 4. Consequently, additional testing of the viscoelastic foams was arranged with Roush Anatrol, a company that specializes in noise and vibration engineering.

Forced-oscillation method

Investigators at Roush Anatrol employed the forced-oscillation technique to evaluate the six foams mentioned above plus a seventh foam called Sun-Mate Med-Soft. They examined each prospective foam to quantify the influence of static preload, dynamic strain amplitude and temperature on modulus of elasticity and damping to serve as input for the analytical model. With the forced-oscillation method, a sinusoidal displacement (strain) was applied to the specimen as the resulting force (stress) and input displacement were measured. Input displacement and output force are complex values with the complex stiffness and phase angle used to define the dynamic properties of viscoelastic materials. Each specimen had a diameter and a height of 12.7 mm (0.5 in.). Three test temperatures, 4°, 21° and 38°C (40°, 70° and 100°F), were selected based on actual temperature readings and knowledge of the mine environment. The chamber temperature was held constant at these temperatures for testing at prestrain levels of 0%, 10% and 45%. At discrete frequencies (ranging from 1 Hz to 100 Hz in 25 Hz steps), data were collected for each temperature. The input strain was controlled to provide the prescribed dynamic strain levels of 0.1%, 1% and 2%. Force and displacement data during the first several oscillations were collected in the time (instead of the frequency) domain. This was necessary to avoid changes in foam properties due to internal heating of the foam over repeated cycling. The dynamic properties of the material were then calculated using the amplitudes of the force and displacement responses with phase angle in the following equations

$E' = [K]F_f (h/S_e) \cos \delta$

$E'' = E' \tan \delta$

Damping = $\tan \delta = E''/E'$

where

$[K]$ is the stiffness modulus (N/m) measured;

δ is the loss angle (degrees) measured;

h is the height of test piece (m);

S_e is the excited surface area on test piece (m^2);

S_l is the lateral surface area of test piece (m^2); and

F_f is the corrective factor, test piece geometry dependent, according to

$F_f = 1/(1 + 2 (S_e/S_l)^2)$

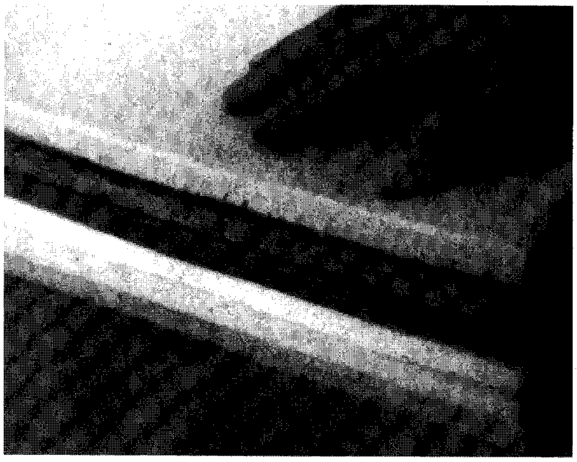
Dynamic modeling

Using a lumped-parameter analytical model, investigators analyzed the foam-isolation system dynamically. The model, which features a seven-degrees-of-freedom spring-mass-damper system, simulated the dynamic interaction of the vehicle, isolation system and operator. A variable mass set on top of a maximum of six layers of viscoelastic foam (with variable thickness) constituted the model.

The ergonomic seat was chosen as the baseline seat in the model because of its known foam configuration and properties. Modulus of elasticity and damping values

FIGURE 3

Initial viscoelastic foam composite for ergonomic seat.



were applied to the model for 10% prestrain on each sample of viscoelastic foam. The entire depth of the foam was assigned a temperature of 21°C (70°F) for the assumed typical day. Several designs were also evaluated with a material temperature of 4°C (40°F) to look at the suitability of the configuration to colder environments.

Using the model, investigators applied a shock impact (from the field data collected) to the isolation system and determined the operator's response for each foam configuration. Responses were generated at the operator/seat interface (seat accelerometer location) and at the operator's torso. These responses were compared to the response of the ergonomic seat measured underground and to the operator's response predicted by the model. An analytical transfer function between the input force and the torso was also generated to show the isolation frequency and the amplification at resonance. In iterative fashion, investigators changed the foam configuration to optimize the seat.

Discussion of results

Extra-Soft, Soft and Pudgee foams exhibited characteristics that make them the best three of the viscoelastic foams evaluated in isolating the shuttle-car operator from jolts and jars. At 4°C (40°F) and 21°C (70°F), the Soft and Extra-Soft have lower modulus of elasticity values than the Yellow, with Extra-Soft the lowest. The Soft and Extra-Soft are relatively stable with temperature and have similar damping properties. Across the temperature range tested, Sun-Mate Pudgee shows less than an order of magnitude change in modulus of elasticity. Across the frequency span and temperature range, the damping properties of Pudgee are also fairly uniform. In addition, Pudgee has the lowest modulus of elasticity values of the seven foams tested. Pudgee's higher damping than the Sun-mate Extra-Soft could, however, restrict its ability to expand from a compressed state during a jolt or shock.

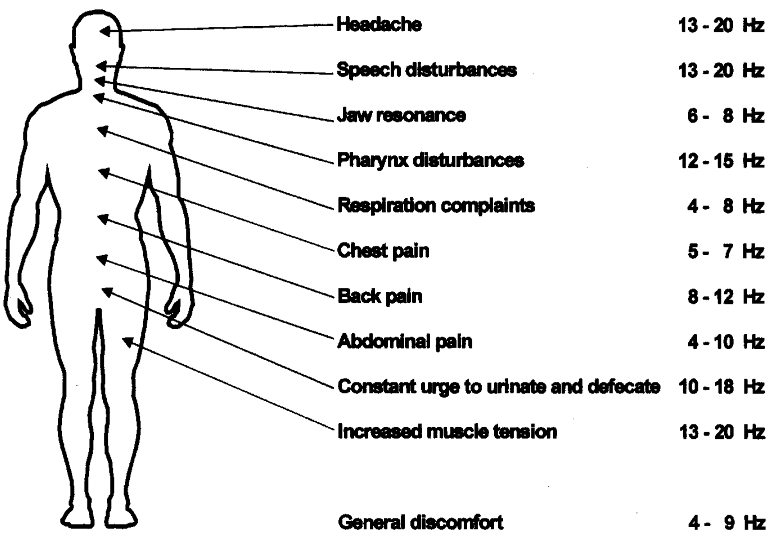
The measured properties of the foams were integrated into the spring-mass-damper model used to represent the seat and operator. A single mass, placed atop the springs and dampers (layers of viscoelastic foams) represented the analytical model of the ergonomic seat tested at the eastern Kentucky mine. Investigators selected this representation because the reclined position of the driver reduces the torso to a single mass. The 50 percentile male, with an upper torso weight of 50.8 kg (112 lbs), was used for the evaluations because the exact weight distribution between the seat pad and the back pad was not known. In-mine measurements of the shuttle car with a full load provided displacement data of the operator deck that was used as the input forcing function to the analytical system.

Investigators evaluated a 127-mm (5-in.) composite of 25.4-mm (1-in.) layers of Extra-Soft and Pudgee. In this composite, the Pudgee was sandwiched between 76.2 mm (3 in.) of Extra-Soft on the bottom and 25.4 mm (1 in) of Extra-Soft on top. This arrangement provided the maximum depth of low-modulus foam, as well as one that maintains its stiffness and damping properties over the expected operating temperature range. The combination also permits a mine or manufacturer the convenience of using only one supplier of foam materials in designing a seat. The isolation characteristics of the seat are improved to approximately 4 Hz (Fig. 5). A small amplification in the 3-Hz region appears due to the lowering of the driver/seat resonance.

Another composite evaluated included a single foam material, 127 mm (5 in.) of Extra-Soft. This design

FIGURE 4

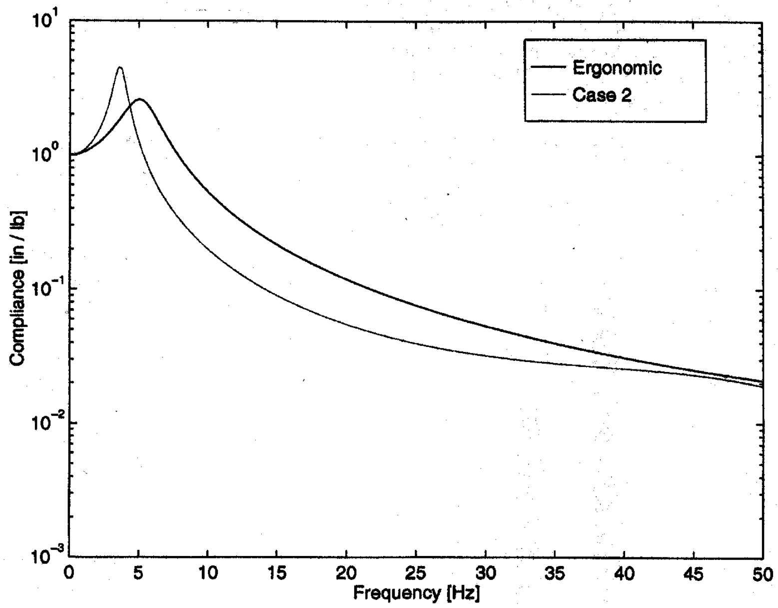
Complaints according to stimulated-vibration frequencies (Magid and Coermann, 1960).



provides the best single viscoelastic foam, in terms of low modulus of elasticity, low and consistent damping and low temperature sensitivity. With the 127-mm (5-in.) Extra-Soft composite, shock isolation is achieved at 5 Hz using the model. Moreover, when analyzing the Extra-Soft composite for the 95% male and 5% female weights, a slight change in the resonance location and in the slope of the mass line occurs, as expected. The lighter operator weight will experience larger displacements at higher frequencies, whereas, a heavier operator will experience the opposite effect.

FIGURE 5

Comparison of shock isolation: initial foam composite (ergonomic) vs. Extra-Soft/Pudgee (Case 2).



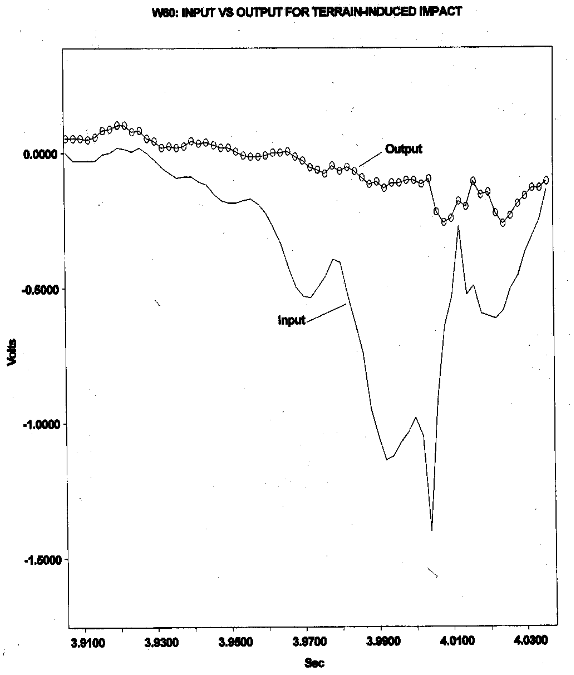
In-mine validation of viscoelastic foams

The effort to validate the effectiveness of the viscoelastic foams Extra-Soft and Pudgee/Extra-Soft was carried out at a deep coal mine near Indiana, PA. RM Wilson Company, who sells seat pad units to underground mines, assisted with data collection by providing the seat pads that included these foam composites. One seat pad unit included five 25.4-mm (1-in.) thick layers of Extra-Soft Sun-Mate for a total thickness of 127 mm (5 in.). The other unit comprised the same except for one 25.4-m (1-in.) thick layer of Pudgee replacing the layer just below the top layer of Extra-Soft Sun-Mate. The two shuttle-car seats in the operator cab of a JOY 10SC were outfitted (over the existing frame) with these seat pads. Data were recorded for the shuttle car operating empty and operating with a full load.

The data analysis gave the following results: For the Pudgee/Extra-Soft composite, the total impact energy reduced was 88.4% in the empty mode, with a transmissibility of 30.3%. Transmissibility was calculated by dividing the root-mean-square (RMS) acceleration of the output signal by the RMS of the input signal (Fig. 6). With a full load, this same foam composite provided a 93.5% reduction in total impact energy to the operator with a 24.2% transmissibility. Similarly, for the Extra-Soft composite, the total impact energy reduced was 91.5% in the empty mode, with a transmissibility of 28.7%. With a full load, the Extra-Soft composite provided a 94.9% reduction in total impact energy to the operator, with a 22.4% transmissibility. These percentages are mean percentages of impacts with sample sizes of 23 and 38 for the empty and loaded tests, respectively, of the Pudgee/Extra-Soft composite and sample sizes of 24 and 34 for the empty and loaded tests, respectively, of the Extra-Soft composite. Impact energy was determined from power-spectral-density (PSD) functions performed on the input signal and the resulting output signal (Fig. 7).

FIGURE 6

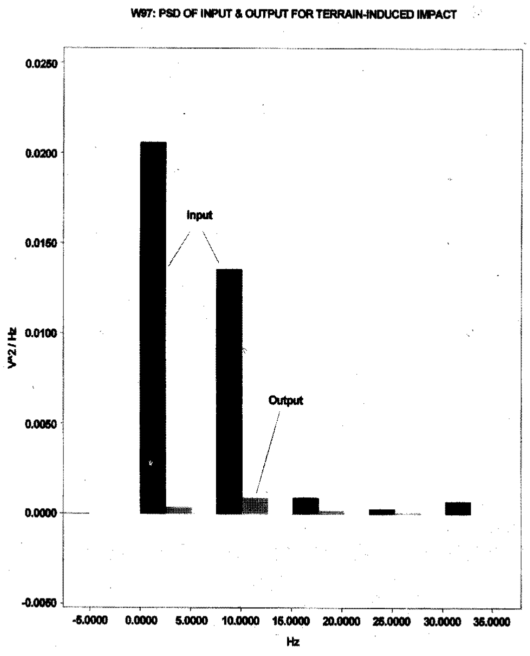
Comparison of input and output signals for a shuttle car traveling empty. Graph illustrates how 127 mm (5 in.) of Sun-Mate Extra-Soft viscoelastic foam attenuates shock impact for a seated operator.



Qualitative information from the mine-safety director further supported the above results. The safety director reported that, since changing to the new seat pads filled with the NIOSH-recommended viscoelastic foams, no complaints of neck or back injuries from mine

FIGURE 7

Power spectral density function of input and output signals from Fig. 6. In this case, a 96.3% reduction in impact energy to the seated shuttle-car operator is achieved with the Sun-Mate Extra-Soft viscoelastic foam.



shuttle-car operators were received. Such reports were frequent prior to using these new foams as seat padding. He also indicated that the pads, which are covered with a polyvinyl/woven-mesh fabric, were holding up well after one year of use.

Summary

The dynamic model provides an analytical tool to design and optimize shock and vibration isolation systems for use on a variety of seating configurations in underground mines. It will aid investigators at NIOSH in providing mining companies and manufacturers with guidelines for the construction of ergonomically designed seats to reduce the shock and WBV exposure for operators of underground mobile equipment. Moreover, the seat padding designs showing the best shock isolation properties for the shuttle-car operator are the Sun-Mate Extra-Soft and Pudgee foam configurations. Analytical results show the Extra-Soft lowers the isolation frequency to 5 Hz, whereas the Pudgee lowers it to 4 Hz. Either of these selections supplies substantially improved isolation performance of the seat in the limited space available, compared to the standard foam-padded shuttle-car seat.

Moreover, underground mine trials with feedback from the mine-safety director demonstrate that the NIOSH-recommended viscoelastic foams are effective at reducing high-energy impacts or shocks. Finally, by substantially reducing the impact energy from jarring and jolting, which is transmitted to seated operators, the NIOSH-prototype seat design and tested-foam seating materials should decrease the immediate and long-term risk of injuries to shuttle-car operators. ■

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