SHOCK REDUCTION FOR LOW-COAL SHUTTLE CAR OPERATORS USING VISCOELASTIC SEATING FOAM

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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 seat suspensions difficult to use in isolating operators from shock and WBV. Researchers at NIOSH, Pittsburgh Research Labatory, are responding to these issues by investigating viscoelastic foams. For the full-load case, an ergonomic seat with viscoelastic foams isolated the shuttle car operator from shock at 15 Hz. Researchers used results from additional foam testing with an analytical model to identify viscoelastic foams that provide shock isolation at a frequency below 5 Hz.

INTRODUCTION

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

The focus of this study was set with the input of underground shuttle car operators. Their most common complaint concerned the jolts and jarring they experienced when traveling over rough bottom. Consequently, the research objectives were to develop a more ergonomically designed seat and identify how well viscoelastic foams of various types and thicknesses reduce the shock impact experienced by shuttle car operators.

FIELD DATA COLLECTION

At a drift mine in eastern Kentucky, NIOSH researchers recorded data on the original seat of a JOY 21SC shuttle car (Figure 1) and a redesigned, version of this seat (Figure 2). The coal seam at the mine is .889 m (35 in) thick with an operating height of approximately 1.09 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, and seat padding composed of viscoelastic foam. Seat padding included six .013-m (½-in) layers of the following configuration from top to bottom:[1] EXTRA-SOFT, PUDGEE, BLUE, YELLOW, SOFT, and GREEN, Figure 3. The BLUE, YELLOW, and GREEN layers were CONFOR medium-density, open-celled polyurethane foams from E-A-R Speciality Composites Corporation, Newark, DE. The EXTRA-SOFT and SOFT are SUN-MATE polyurethane foams with organic composition of more than 50% plant derivatives. SUN-MATE

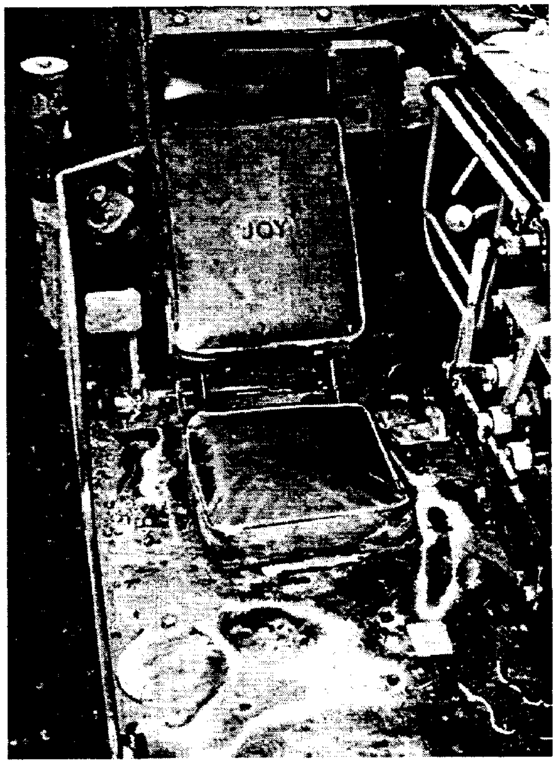

Figure 1. Original seat.

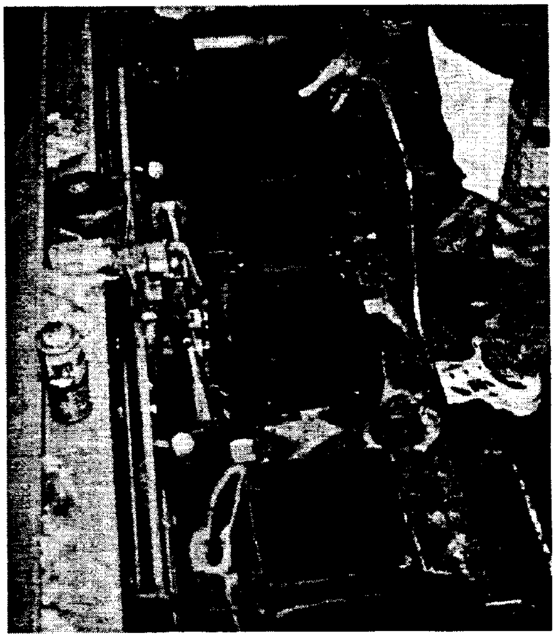

Figure 2. Ergonomic seat.

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[1] Reference to specific products does not imply endorsement by NIOSH.

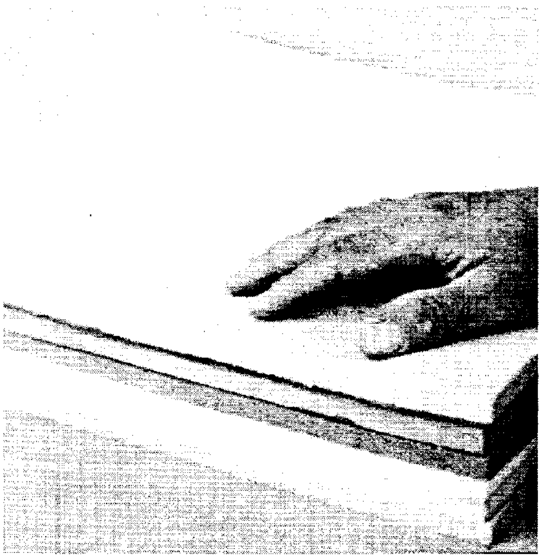

Figure 3. Initial viscoelastic foam composite for ergonomic seat.

PUDGEE is a viscoelastic gel-foam with a unique composition and soft dough-like consistency.

Data were recorded with the shuttle car operating empty and with a full load along a typical stretch of roadway. 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, Figure 4. Consequently, additional testing of the viscoelastic foams was arranged with a company that specializing in noise and vibration engineering, Roush Anatrol.

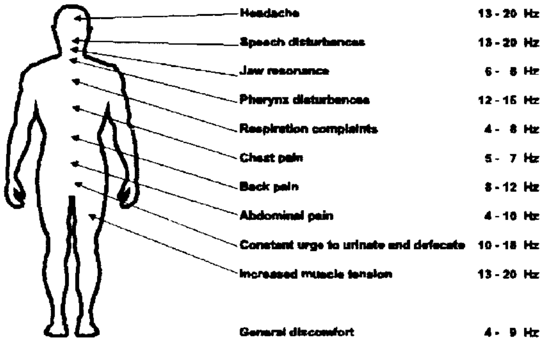

Figure 4 - Complaints according to stimulated vibration frequencies, Magid and Coermann (1960).

FORCED OSCILLATION METHOD

Investigators at Roush Anatrol employed the forced oscillation technique to evaluate the six foams above and a seventh (SUN-MATE MED-SOFT). They examined each prospective foam to quantify the influence of static pre-load, 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. The size of each specimen was .013 m (1/2 in) diameter with a .013 m (1/2 in). Three test temperatures [4.4 °C (40° F), 21.1° C (70° F), and 37.8 °C (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 pre-strain levels of 0%, 10%, and 45%. At discrete frequencies (from 1 Hz to 100 Hz in 25 Hz steps), data was collected for each temperature. The input strain was controlled to provide the prescribed dynamic strain levels of .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:

$$E' = [K]\, F_l\, (h / S_c)\cos\delta$$

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

$$\text{Damping} = \tan\delta = E'' / E'$$

Where,

$[K]$ = stiffness modulus (N/m) - measured

δ = loss angle (degrees) - measured

h = height of test piece (m)

S_c = excited surface area on test piece (m^2)

S_l = lateral surface area of test piece (m^2)

F_l = corrective factor, test piece geometry dependent

$$F_l = 1 / (1 + 2 (S_c / S_l)^2)$$

DYNAMIC MODELING

Using a lumped-parameter analytical model, investigators analyzed the foam isolation system dynamically. The model, which features a seven degree of freedom spring-mass-damper system, simulated the dynamic interaction of the vehicle, isolation system, and operator. A variable mass atop a maximum 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 were applied to the model for 10% pre-strain on each sample of viscoelastic foam. The entire depth of the foam was assigned a temperature of 21.1° C (70° F) for the assumed typical day. Several designs were also evaluated with a material temperature of 4.4° 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 4.4° C (40° F) and 21.1° 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 upper torso weight of 50.6 kg (112 lbs), was used for the evaluations since 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-m (5-in) composite of one-inch layers of EXTRA-SOFT and PUDGEE. In this composite, the PUDGEE was sandwiched between .076 m (3 in) of EXTRA-SOFT on the bottom and .025 m (1 in) of EXTRA-SOFT on top. This arrangement provided the maximum depth of a 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 (Figure 5). A small amplification in the 3 Hz region appears due to the lowering of the driver/seat resonance.

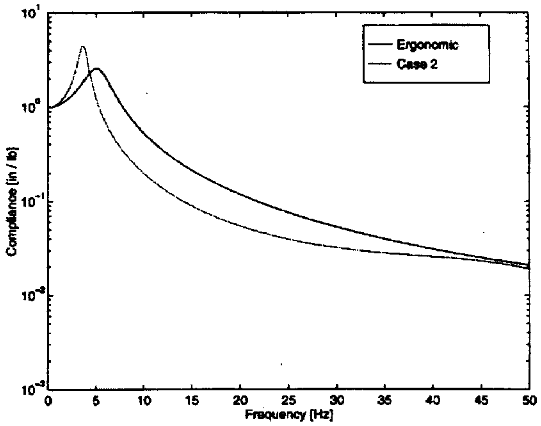

Figure 5 - Comparison of shock isolation: initial foam composite (Ergonomic) versus EXTRA-SOFT/PUDGEE (Case 2).

Another composite evaluated included a single foam material, .127 m (5 in) of EXTRA-SOFT. This design provides the best single viscoelastic foam, in terms of low modulus of elasticity, low and consistent damping, and low temperature sensitivity. With the .127-m (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

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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 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. 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. Although, feedback from a shuttle car operator indicates the PUDGEE composite, because of its higher damping, may lessen (more so than the EXTRA-SOFT) the displacement the operator experiences when jarred.

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