The evolution of drill bit and chuck isolators to reduce roof bolting machine drilling noise

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Abstract

Among underground coal miners, hearing loss remains one of the most common occupational illnesses. To address this problem, the U.S. National Institute for Occupational Safety and Health Office of Mine Safety and Health Research (NIOSH OMSHR) conducts research to reduce the noise emission of underground coal mining equipment, an example of which is the roof bolting machine. Field studies show that, on average, drilling noise is the loudest noise that roof bolting machine operators would be exposed to, and it contributes significantly to the operators' noise exposure. OMSHR has determined that the drill steel and chuck radiate a significant amount of noise during drilling. OMSHR and the Corry Rubber Corporation (CRC) have developed a bit isolator that breaks the steel-to-steel link between the drill bit and drill steel and a chuck isolator that breaks the mechanical connection between the drill steel and the chuck. This effectively reduces the noise radiated by the drill steel and chuck and in turn reduces the noise exposure of roof bolter operators. This paper documents the evolution of the bit isolator and chuck isolator. Laboratory testing confirms that production bit and chuck isolators reduce the A-weighted sound level generated during drilling by 3.7 to 6.6 dB.

Introduction

Hearing loss prevention is one of 21 priority research areas listed in the the U.S. National Institute for Occupational Safety and Health (NIOSH) national occupational research agenda (NIOSH, 1996). Further, the U.S. Department of Labor's Mine Safety and Health Administration (MSHA) collects noise sample data that assists OMSHR in selecting equipment whose operators are most likely to be overexposed to noise (MSHA, 2005). Sample data collected from 2000 to 2005 show that seven types of machines compose the bulk of the equipment whose operators exceed 100% noise dose per the MSHA permissible exposure level (PEL) (Table 1). Among operators of all equipment used in underground coal, the table shows that roof bolting machine (RBM) operators were the second most numerous group of miners to be overexposed to noise.

To develop effective noise controls, it was important to determine the tasks and noise levels associated with significant noise exposure for roof bolting machine operators. The objective was to reduce operators' noise exposure to a time-weighted average (TWA) of 90 dB(A) or less for an eight-hour shift. This would correspond to a noise dose of 100%—the maximum allowed per the MSHA PEL. OMSHR performed noise dosimetry and time-motion studies to determine the noise doses and sound levels associated with the typical tasks required of RBM operators and the time spent conducting these tasks. Post-processing of this data revealed the tasks that operators devoted the most time to, the noise dose accumulated during each task and, of course, the tasks which are the primary contributors to the operators' noise exposure. This information helped OMSHR to determine where noise control research should be focused.

Tables 2 and 3 summarize data collected during a time-motion study of a dual-boom J.H. Fletcher roof bolting machine (Peterson and Alcorn, 2007). The tasks shown are those for which the operators were engaged at least 1% of their shift. The 'other' category of Tables 2 and 3 includes time spent riding the elevator, when the operators were bolting alone,

Table 1 — Percentage of noise overexposures by machine.	
Machine	**%**
Continuous mining machine	35
Bulldozer	24
Roof bolting machine	17
Front end loader	8
Shuttle car	6
Auger miner	5
Truck	5

Table 3 — PEL dose by task, %.		
Task	**Operator 1**	**Operator 2**
Both drilling and bolting	52	68
Drilling alone	2	4
Riding mantrip	8	21
Tramming	11	18
Lunch	0	2
Prep time	5	9
Other	0	7
Total	78	127

Table 2 — Time spent by task, minutes.		
Task	**Operator 1**	**Operator 2**
Both drilling and bolting	218	218
Drilling alone	7	10
Riding mantrip	28	28
Tramming	63	63
Lunch	54	54
Prep time	108	108
Other	241	239

Table 4 — Equivalent TWA sound level, dB(A).		
Task	**Operator 1**	**Operator 2**
Drilling	90	95
Bolting	70	86

Figure 1 — Drill steel accelerometers and slip ring assembly.

both drilling or both bolting, and other times where the activity could not be documented. Table 2 shows that the operators spent a significant amount of time drilling and bolting simultaneously—roughly 3.5 hours of the shift. As shown in Table 3, Operator 1 accumulated 52% PEL dose during this time, or two-thirds of his daily noise exposure, 78% PEL dose. Operator 2 accumulated 68% PEL dose during this time, or greater than half of his full-shift exposure of 127%. Further analysis showed that drilling sound levels far exceeded those associated with the bolting portion of the duty cycle (Table 4).

With ordinary drilling times and relatively short bolting times for resin-type roof bolts, the operators spent significantly more time drilling than bolting. These observations confirmed the initial expectation that for the RBM, the drilling portion of the operators' duty cycle exposed them to the highest noise levels and was the most significant contributor to the operators' noise dose. Thus, if noise controls were to be effective at reducing RBM operator noise exposures, then drilling noise must be reduced.

In percussive rock drilling, one notable source of noise generation is drill steel vibration (Hawkes and Burks, 1979; Carlvik, 1981). There are three fundamental ways to reduce these vibrations and, thus, noise: reduce the source of the vibration, attenuate the vibration or attenuate the noise. To this end, OMSHR first sought to quantify the vibration levels of the RBM components associated with drilling. These included the drill head, slinger plate, drill guide, drill steel and the drill media.

Figure 1 shows a slip ring assembly to interface drill steel acceleration signals with data acquisition equipment. Figure 2 shows acceleration levels measured on a hexagonal drill steel while drilling with a 35-mm-diameter bit during a five-second sample (rotation speed of 200 rpm and thrust of 9.4 kN). OMSHR used granite as the drill media to represent high compressive strength roof and because this compressive strength should remain consistent throughout the drilling, which helps ensure test repeatability. Levels peaked at more than 500 g, confirming significant drill steel vibration during drilling.

To locate noise sources near the drill steel area, OMSHR used a 42-microphone Bruel and Kjaer beamforming array and associated data acquisition system and analysis software. To measure operator ear sound levels, an additional microphone was placed near the RBM operator's head. Granite was used as the drill media for the aforementioned reasons.

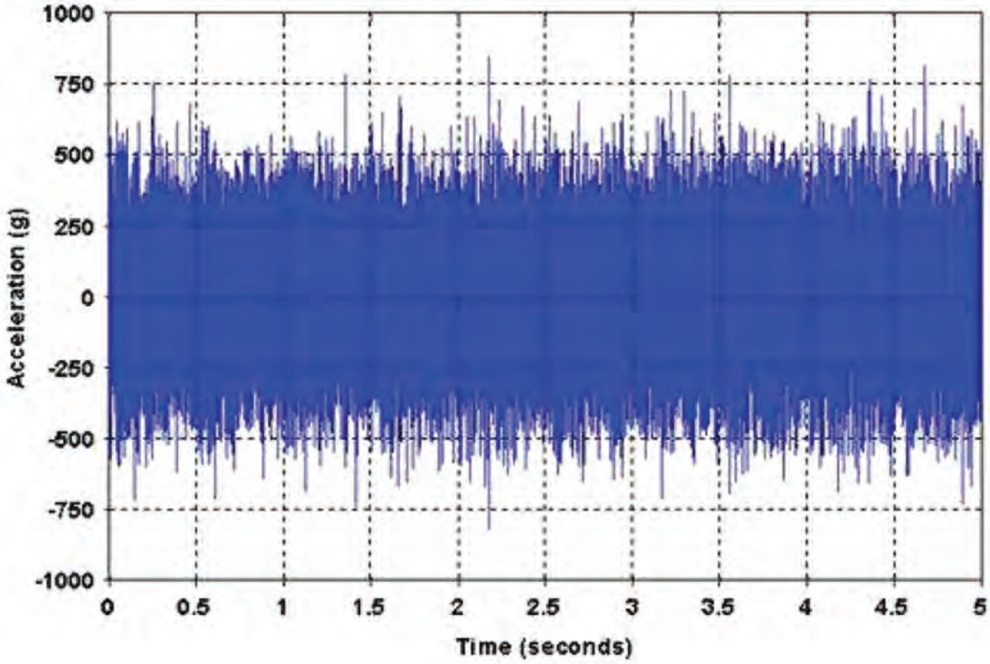

Figure 2 — Typical drill steel acceleration, hexagonal drill steel, 35-mm-diameter bit, granite drill media.

Figure 3 — Jaw-type coupling with 58 Shore D urethane spider.

Figure 4 — Beamforming results for baseline drilling, 100 dB(A) at the operator's position.

A jaw-type shaft coupling with a 58 shore D durometer spider was used to test the premise that reducing the mechanical coupling between the drill steel and the chuck would reduce sound levels at the operator's ear position (Fig. 3). Using the jaw-type coupling reduced the sound level at the operator's position from a baseline of 100 dB(A) to 96 dB(A) for 9.4 kN of thrust and from 104 dB(A) to 100 dB(A) for 22 kN of thrust.

Additional testing using the beamforming array showed that the steel radiates a significant amount of noise during drilling. Figure 4 shows baseline data collected using a thrust of 9.4 kN. The noise sources are centered roughly 100 to 200 mm (4 to 8 in.) below the drill steel-media interface and above the chuck. As the drill steel advances during drilling, the lower noise source moves with the chuck, while the upper source essentially remains just below the media. Figure 5 shows beamforming results with the inclusion of the jaw-type coupling with the same operating conditions. In Figs. 4 and 5, light colors indicate areas of high noise radiation while dark

Figure 5 — Beamforming results for drilling with the jaw-type coupling, 96 dB(A) at the operators' position.

colors indicate areas of lower noise radiation. Given these results, vibration isolation is a viable option to reduce noise generation during RBM drilling.

Further development of a vibration isolator for drilling with RBMs required the aid of a collaborating partner proficient in the design and production of vibration isolators. Therefore, OMSHR began working with Corry Rubber Corporation (CRC) on bit and chuck isolators.

Design overview

The final isolator designs are shown in Fig. 6. These designs evolved from several prototype designs that were evaluated for noise attenuation and durability. There are three main parts to each: the inner steel member, the outer steel member and the elastomer. The elastomer, which is between the inner and outer steel members, provides the vibration isolation. Some of the earlier designs consisted of a bonded joint (elastomer bonded to an inner member), which was subsequently assembled into an outer member. These precompressed, bonded joint designs utilize a postvulcanization (PV) bond between the outer surface of the elastomer and the inner surface of the outer steel member to react cutting forces. Advantages of precompressed bonded joint designs include improved elastomer durability (after assembly, the elastomer is in compression) and ease of manufacture, since the mold has to accommodate only one metal and, therefore, one bond.

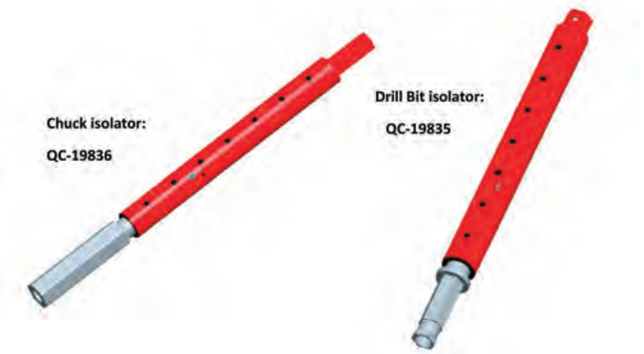

Figure 6 — Final production designs of isolators for use with 35-mm-diameter drill bits.

While these designs offered sufficient noise attenuation, they did not meet the load carrying requirements, due to the relatively low bond strength and variability associated with PV bonds. The current production designs are fully bonded designs, which means the elastomer is bonded to the metal components during the molding operation, thus eliminating the need for a PV bond. Based on lab testing, the production designs provide outstanding noise attenuation while meeting all load requirements.

A typical cross section of the production isolator design is shown in Fig. 7. The outer and inner members are machined out of 4130/4140 steel and heat-treated to 350 BHN. Sound level measurements were conducted with various elastomers to examine the attenuation as a function of elastomer properties. However, the production elastomer will more than likely be a 50 to 55 durometer (Shore A) natural rubber (NR) blend. The bonded length of 254 mm is consistent across all designs and necessary to safely withstand the drilling forces applied to the bonds between the elastomer and the metal members. An 11.4-mm gap protects the isolator from overload, since the outer member will bottom out against the inner member shoulder at roughly 45 kN. Any load above 45 kN will then be reacted by the metal components instead of the elastomer.

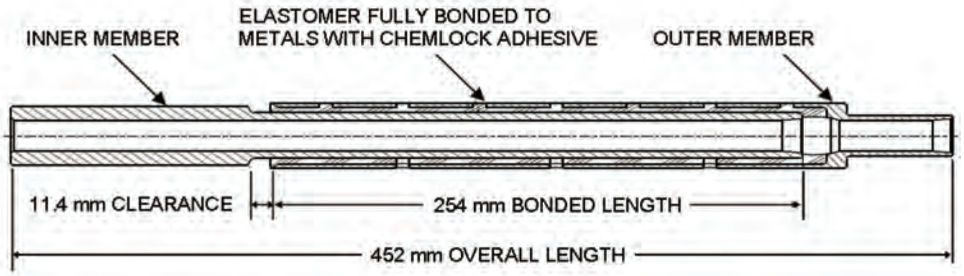

Figure 7 — Cross section of production design chuck isolator.

Figure 8 — Isolators bonded with elastomers from Table 5.

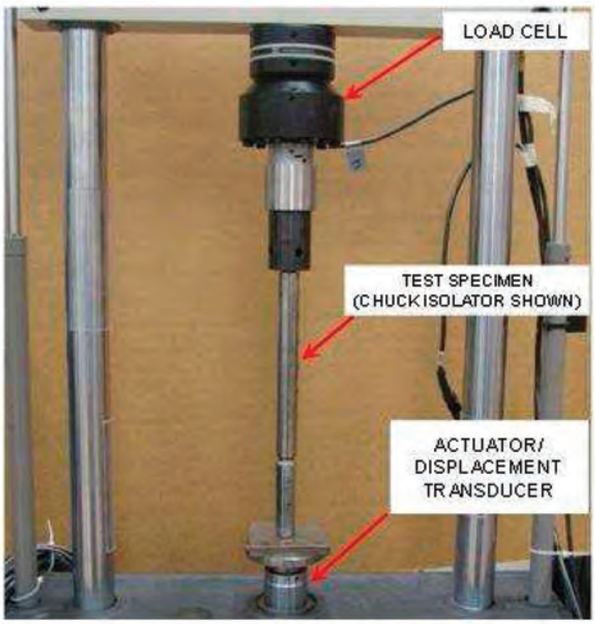

Figure 9 — MTS810 test system used to measure axial load capacity and static and dynamic stiffness.

Design requirements for the 35-mm isolator are summarized as follows:

1. Max torque: 410 N-m
2. Max axial load (thrust load): 35 to 45 kN
3. Isolator metals will bottom out at 11.4 mm deflection or approximately 45 kN thrust load
4. Preliminary life requirement: 2 weeks to 1 month of continuous operation
5. Estimated static axial stiffness (for noise attenuation): 2,600 kN/m to 5,200 kN/m

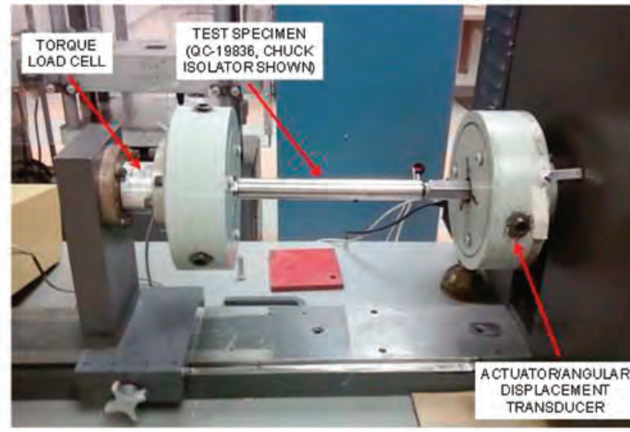

Figure 10 — Apparatus used for testing torsional load capacity and static torsion stiffness.

6. Estimated torsional static stiffness (for noise attenuation): 6.8 to 20.3 N-m/deg.

The stiffness requirements were based on sound level measurements using prototype isolators. The sound level at the operator's ear was measured during "normal" drilling and also with several prototype isolator parts of varying stiffness. The production designs meet the requirements listed above. Extensive lab testing and analysis were performed on the production design to verify these requirements.

Elastomer compound evaluation

Several isolators were made with various elastomer compounds (Fig. 8). These elastomers were selected to provide a broad range of dynamic and static properties for sound level evaluation while still satisfying the requirements outlined above. A description of each elastomer compound evaluated is shown in Table 5.

The natural rubber compounds used for the isolators have a range of tensile modulus values from 1.6 MPa (45 durometer compound) to 4.1 MPa (68 durometer compound). The butyl compound provides approximately the same static stiffness as the 45 durometer natural rubber, with four times as much damping. Furthermore, the 58 durometer and 45 durometer natural rubber compounds have nearly the same damping but different stiffness. The goal was to explore the effects that damping and stiffness have on noise attenuation.

Lab testing

Isolators bonded with the elastomers detailed in Table 5

Table 5 — Evaluated elastomer compounds listed by CRC compound number and description.

100 Modulus (MPa)	Elongation (%)	Tensile (MPa)	Durometer (Shore A)	Damping loss factor [a]
		M-350-40 (45 durometer NR)		
1.6	569	22.4	45.3	0.09
		M-460-2 (58 durometer NR)		
2.7	438	20.8	59.2	0.10
		M-370-35 (68 durometer NR)		
4.1	360	25.8	67.7	0.17
		M-660-1 (50 durometer butyl rubber)		
1.1	807	16.8	48.3	0.44

[a] (tan del), 10 Hz / + 20% strain

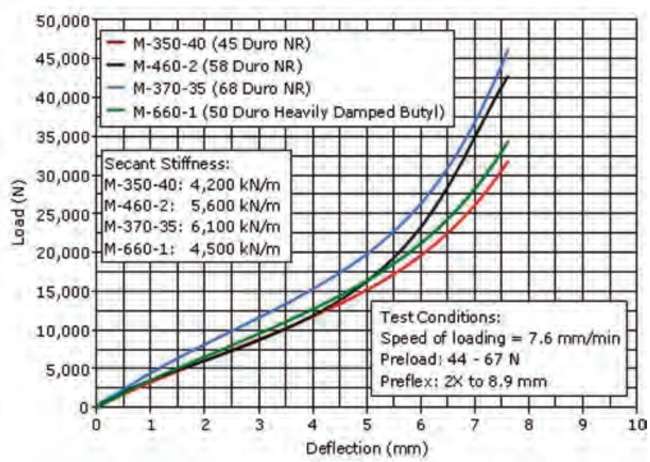

Figure 11 — Axial static load-deflection curves.

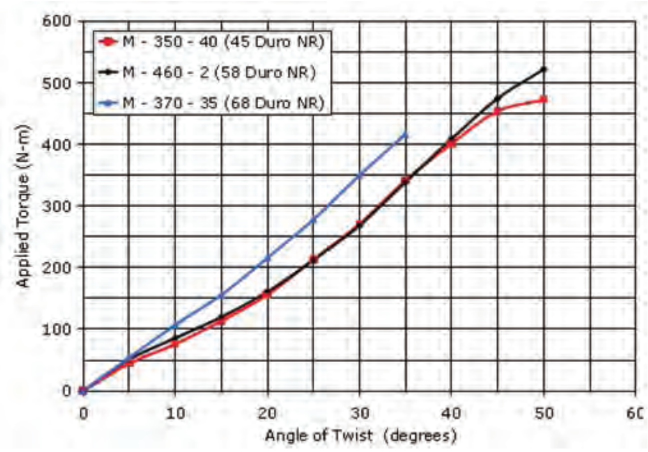

Figure 13 — Static torque vs. angle of twist.

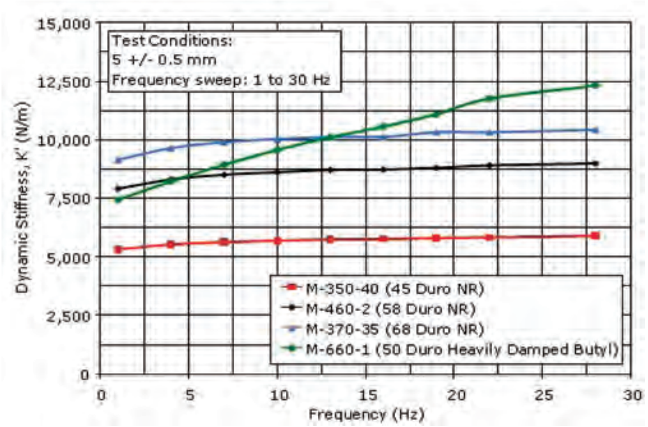

Figure 12 — Dynamic axial stiffness, *K*′, vs. frequency.

were tested in the lab both in the torsion and axial directions. The machines used for this testing are shown in Figs. 9 and 10. The purpose of this testing was to verify that stiffness and load requirements were met. A summary of all the testing completed with results follows.

1. Axial static stiffness – record load up to 7.6 mm deflection (see Fig. 11.)
2. Axial static stiffness– load in the axial direction to 18 kN.
3. Dynamic stiffness at 5 +/- 0.5 mm – perform frequency sweep from 1 Hz to 30 Hz in 3-Hz increments. Record dynamic stiffness, *K*', damping stiffness, *K*'', and loss factor (tan del). (See Fig. 12 for dynamic stiffness, *K*', versus frequency.)
4. Torsion test to approximately 410 N-m (the design torque requirement) and record torque versus angular deflection curve (see Fig. 13.)
5. Torsion test one sample to failure to determine failure torque.

Summary table and discussion of results

Axial static and dynamic stiffness and torsional stiffness for all the isolators tested are summarized in Table 6. From these results, some general observations can be made:

1. Measured stiffness (both axial and torsional) is consistent with the durometers specified in Table 1 for each compound. In other words, the 68-durometer NR has the highest torsional and axial stiffness, followed by the 58-durometer and then the 45-durometer compounds.
2. All measured stiffness values meet design requirements and were verified with finite element analysis (FEA) and hand calculations.
3. The 50-durometer, heavily damped butyl is shown to be highly frequency sensitive (see Fig. 12). While the

Table 6 — Stiffness results summary. Elastomers listed by compound number (CRC designation) and description.

Axial static (secant) stiffness at 7.6 mm (kN/m)	Axial static (secant) stiffness at 18 kN (kN/m)	Axial dynamic stiffness 10 Hz, + 0.5 mm (kN/m)	Torsional (secant) stiffness at 410 N-m (N-m/deg)
M-350-40 (45 durometer NR)			
4,200	3,100	5,600	9.5
M-460-2 (58 durometer NR)			
5,600	3,400	8,600	10.2
M-370-35 (68 durometer NR)			
6,100	4,000	10,200	11.9
M-660-1 (50 durometer butyl rubber)			
4,500	3,300	9,600	TBD

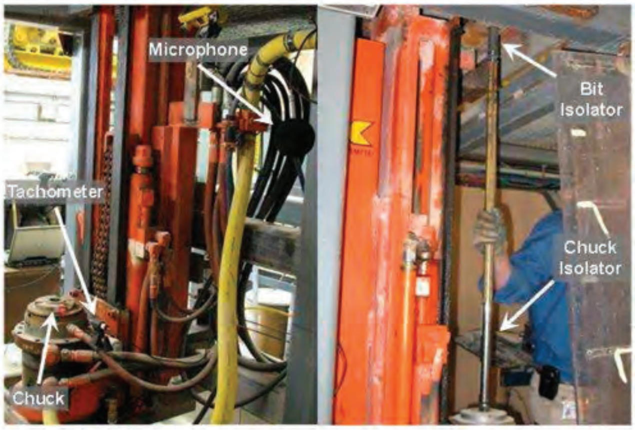

Figure 14 — Test setup for sound level measurements at the operator's ear.

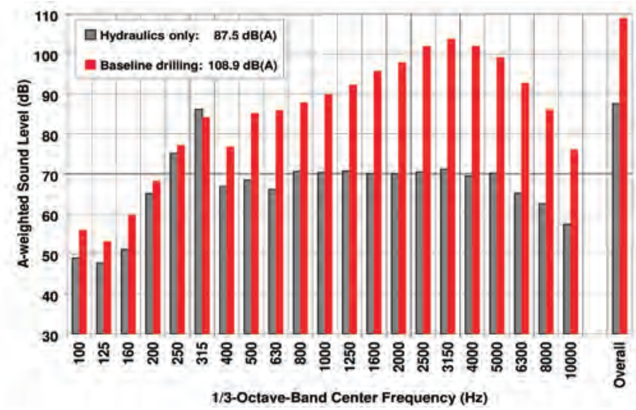

Figure 15 — A-wtd sound level in 1/3-octave bands for hydraulics and baseline drilling conditions.

Table 7 — Test configurations for sound level measurements.		
Test	**Bit isolator**	**Chuck isolator**
BG	not applicable	not applicable
HYD/VAC	not applicable	not applicable
BASE	not applicable	not applicable
T1	45 durometer NR	none
T2	45 durometer NR	45 durometer NR
T3	58 durometer NR	none
T4	none	58 durometer NR
T5	58 durometer NR	58 durometer NR
T6	68 durometer NR	none
T7	68 durometer NR	68 durometer NR

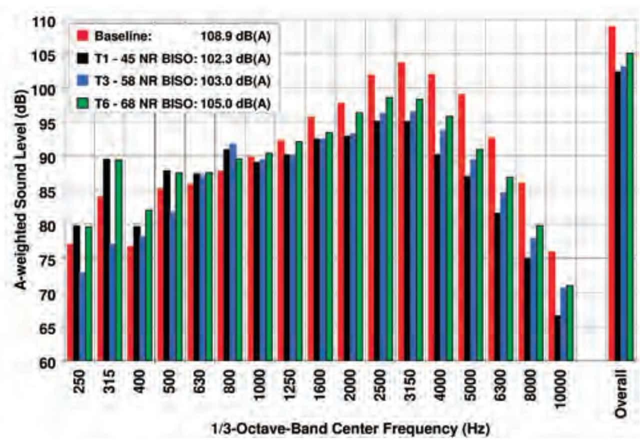

Figure 16 — A-wtd sound level in 1/3-octave bands for baseline and with bit isolators.

static stiffness is nearly the same as for the 45-durometer natural rubber, the dynamic stiffness, *K*', at 30 Hz is more than twice as high. This sort of behavior (frequency sensitivity) is typical of heavily damped elastomer compounds. The noise and vibration benefits from high damping may be offset by the higher dynamic stiffness at higher frequencies.

4. Load requirements of 45 kN axial and 410 N-m torsion were met by all isolators. The metal components showed no evidence of yielding and the elastomers showed no evidence of tensile failure or bond failure at these loads. Additionally, two isolators were loaded to failure on the torsion machine, with failure torques of 730 N-m and 760 N-m, which are nearly twice the torque requirement.

Laboratory sound level measurements

A computer-controlled drilling apparatus (see Fig. 14) was used to test the bit and chuck isolators made with the natural rubber compounds. The butyl rubber parts could not be tested, because the vacuum system on the test apparatus failed prior to testing the butyl parts. This caused the drill steel to become clogged and the drill head to stall. Table 7 shows the tests performed with and without drilling. An optical tachometer was used to check the rotational speed for each test. A Bruel & Kjaer Type 4188 microphone was positioned roughly 1 m from the drill steel at a height of 1.5 m. An LMS Pimento portable data acquisition system was used to record the sound pressure using 24-bit resolution at 20,000 samples/second. The microphone data were postprocessed to calculate the A-weighted 1/3-octave-band sound levels according to ANSI standards (ASA, 2009).

For all testing, 35-mm-diameter drill bits were used with hexagonal drill steels to drill into a granite block. A 1.4-m-long drill steel was used for baseline measurements. When the bit and chuck isolators were tested, shorter drill steels were used to maintain a total length of 1.4 m. Measurements with either a bit isolator or a chuck isolator were performed using a 1.0-m-long drill steel, while measurements with both a bit isolator and a chuck isolator were completed with a 0.7-m-long drill steel. All tests were performed with a rotational speed of 270 RPM, a penetration rate of 28 mm/sec and a maximum thrust of 22 kN. These parameters were selected based on prior experience showing that lower rotation speeds yield improved bit life when drilling into high compressive strength material, such as granite. For each configuration, two holes were drilled and the data for each hole were averaged. For the two measurements of a given configuration, the minimum and maximum differences in the overall A-weighted sound levels were 0.3 dB and 2.2 dB, respectively.

Prior to performing measurements with drilling, the sound pressure was measured with only the hydraulic and vacuum systems operating. Figure 15 shows the A-weighted sound levels in 1/3-octave bands with the hydraulics and vacuum

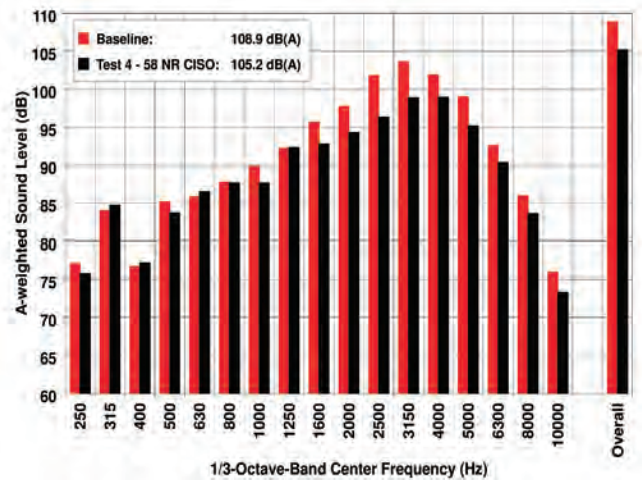

Figure 17 — A-wtd sound level in 1/3-octave bands for baseline and with only a 58 duro NR chuck isolator.

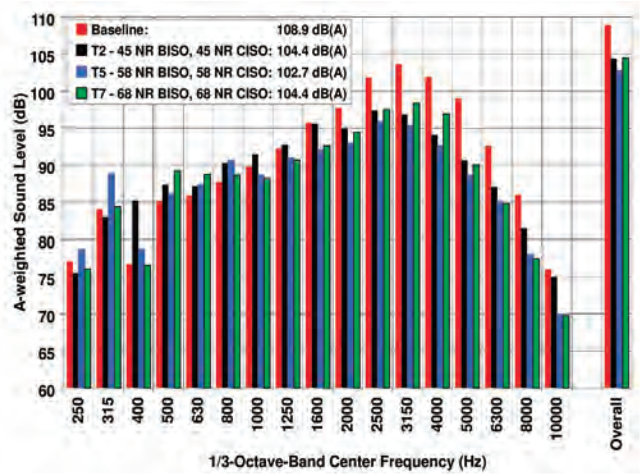

Figure 19 — A-wtd sound level in 1/3-octave bands for baseline; 45 duro NR BISO and CISO; 58 duro NR BISO and CISO; and 68 duro NR BISO and CISO.

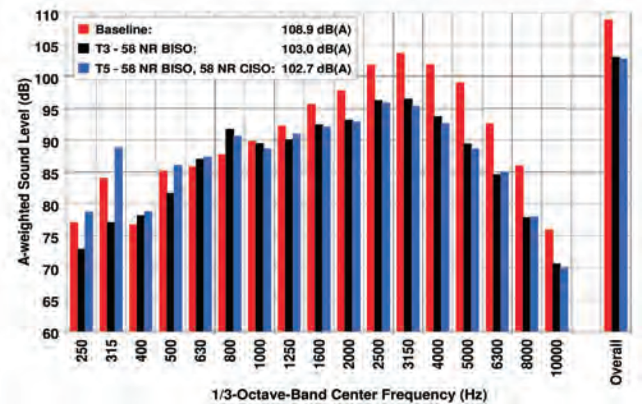

Figure 18 — A-wtd sound level in 1/3-octave bands: baseline; 58 duro NR BISO; and 58 duro NR BISO with 58 duro NR CISO.

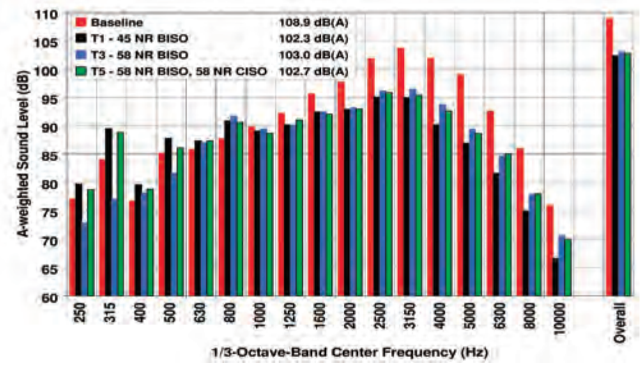

Figure 20 — A-wtd sound level in 1/3-octave bands for baseline and best three tests: 45 duro NR BISO; 58 duro NR BISO; and 58 duro NR BISO with 58 duro NR CISO.

systems and for drilling with a 1.4-m-long hex drill steel. The figure clearly demonstrates that noise from the hydraulics and vacuum are insignificant compared to drilling noise. The figure shows that the levels in the 400 Hz through 10 kHz 1/3-octave-bands increase by 10 dB or more with drilling. In addition, the levels at and below 315 Hz change very little, suggesting that the noise at these frequencies can be attributed to the hydraulics and vacuum rather than drilling. Finally, the figure shows that the highest in-band levels are in the 2,500, 3,150 and 4,000 Hz 1/3-octave bands. The remaining figures will focus on the levels above 250 Hz, because drilling noise does not have significant low frequency content.

Figure 16 shows the A-weighted sound level spectra for the tests with bit isolators compared to the baseline test case. The figure shows that each of the bit isolators significantly reduced drilling noise above 1,600 Hz. The 45-durometer bit isolator achieved the highest reductions while the 68-durometer bit isolator yielded the least reductions. The 45-, 58- and 68-durometer bit isolators reduced the overall A-weighted sound level by 6.6, 5.9 and 3.9 dB, respectively. Because the reduction increased as the durometer decreased, and the stiffness of a rubber component decreases as the durometer decreases, the data suggest that decreasing the stiffness of the bit isolator could further reduce the sound level. However, reducing the durometer could also have a negative impact on the life of the part.

A single test was conducted with a chuck isolator only. Figure 17 shows the resulting spectra for the baseline compared to the test with a 58 durometer chuck isolator. The figure shows that the chuck isolator substantially reduced the levels above 1,600 Hz and reduced the overall A-weighted sound level by 3.7 dB.

Figure 18 shows the resulting 1/3-octave band spectra for drilling with a 58 durometer bit isolator and with both a 58 durometer bit isolator and chuck isolator. The figure shows a marginal additional reduction of the in-band levels for some frequencies. However, the changes are so small this could be test-to-test variation.

Combinations of bit and chuck isolators of the same durometer were tested to explore their effect on the noise generated by drilling. Figure 19 shows the results for these combinations along with the results for baseline conditions. The figure shows that the levels with the 58 durometer isolators are lower than those with either the 45 or 68 durometer isolators. This is somewhat surprising, since isolation usually improves as stiffness is reduced. However, the figure shows that the combination of the least stiff isolators—the 45 durometer parts—resulted in higher levels. This could be a result of the lower stiffness chuck isolator allowing the drill steel to drill an out-of-round hole. This would tend to cause the sides of the drill steel to rub against the drill medium, which would in turn increase noise. Future testing should explore using a low stiffness bit isolator in combination with a wide range of chuck isolators to fully examine this phenomenon.

Figure 20 shows the results for the best three tests with isolators along with the baseline results. The figure shows that using a 45-durometer bit isolator resulted in the greatest reductions. However, each of these tests resulted in substantial sound level reductions in the 1/3-octave bands at and above 1,600 Hz.

Conclusions

The current designs of production bit and chuck isolators evolved from relatively simple isolation devices that were only suitable for laboratory testing. The production designs were verified to meet design targets for spring rate, torque and load capacity and sound level reduction. Sound level measurements collected using an automated drilling apparatus showed that bit and chuck isolators with natural rubber elastomers reduced the sound level near the drill steel. While all the tested isolators reduced the A-weighted sound level whether used singly or in combination, the 45-durometer natural rubber bit isolator achieved the highest reduction, 6.6 dB, while the 58-durometer natural rubber bit isolator yielded a reduction of 5.9 dB. Measurements with a combination of a bit isolator and chuck isolator revealed that the sound level could increase compared to isolator-only values if the stiffness of the chuck isolator is low. This suggests that there is an optimal stiffness for the chuck isolator.

Disclaimer

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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