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Intermittent Modal Vibration and Squeal Sounds Found in Electric Motor-Operated Seat Adjusters

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ABSTRACT

Two years after the start of production, some members in a family of power seat adjusters developed an intermittent loud squeal sound when operated in the vehicle. An exhaustive and comprehensive engineering analysis identified the noise source to be primarily a single component in the seat track which was excited under specific conditions to vibrate in its free - free natural resonant frequency mode. The component was identified as the horizontal lead screw which vibrated under stick-slip principles against mating hardware. The noise was not reproducible in any consistent way; therefore, it was not readily detectable with 100% serial testing. Several solutions were enacted for controlling the problem in the short term while an investigation to the root cause was completed. Three long term solutions which addressed the root cause were pursued in parallel up to the production release of the best solution. By means of designed experiments, frequency analysis and systems engineering principles, a newly designed drive nut, having two added degrees of freedom of motion, provided the robustness needed to eliminate the squeal 100% of the time while serving the customers with a safe and secure solution.

INTRODUCTION

Any audible extraneous sound heard while driving in a motor vehicle is usually considered annoying. Moreover, such unusual sounds are often viewed by the operator as a precursor to something much more serious, and thus cause for alarm. When these sounds originate in the engine compartment, in the brake system, or in the steering mechanism, the car usually goes to the garage immediately because the security of the vehicle is in doubt. However, squeaks, rattles and noises in other parts of the car will often be tolerated during the short term but treated later, once the car has accumulated some miles.

Using sound to analyze equipment problems has been used for many years. For example, roller bearings installed in rotating equipment make characteristic sounds depending on the amount of equipment usage as well as its lubrication history. Often, the machine operator can predict when a piece of equipment will break down based on his or her experience with its characteristic sounds. Furthermore, the military has used a field of expertise called PROGNOSTICS, which is founded on vibration, temperature and sound, to predict the degree of wear and the operational readiness of its might and muscle.

It's no wonder then, when a power seat adjuster in the family car emits a loud mechanical squeal, the owner would more than likely respond with concern. While operational failure of a seat adjuster would not be life threatening, a failure nevertheless could lead to a greater inconvenience and expense.

Included as part of the OEM requirements is that a seat adjuster operate smoothly, without vibration and without unusual noise. The practical side of this requirement, nearly universally understood, is that automotive supplied products need to also be low in price. However, high precision demanded during part fabrication is normally contrary to high feeds and speeds which are desired for the efficient manufacturing process. Consequently, the price competitiveness of the supplied product leads to piece to piece geometrical tolerance variation. Such variation in itself is not bad, but in a system that comprises many individual components, sometimes unique interactions, due to that tolerance variation can lead to some surprises. In the case at hand, after being in production for more than two years, the customer reported that a series of seat adjusters emitted intermittent squeal sounds when operated under certain constrained conditions. The squeal could be heard only if the seat track was solidly fixtured and adjusted to the upmost vertical position and then moved rearward from the most forward position. Only under those physical constraints would the sound be generated, and then only sometimes would it occur. That unusual intermittent squeal sound was indeed annoying and could easily be considered by the owner as a precursor to something much worse happening. This paper describes the engineering task of determining the root cause for the squeal sound and the events leading to a cost effective and safe solution to the problem.

TECHNICAL BACKGROUND AND PRODUCT DESCRIPTION

A power seat adjuster is an electric motorized mechanism that is placed between the seat frame and the floor pan of an automobile. Its principle function is for the convenience of the operator in order to locate his or her body in an optimum position relative to the windows, the steering wheel and the foot pedals. Moreover, in the case of a crash event, the seat adjuster must hold the seat and the occupant firmly and without fracture inside the passenger compartment. In recent years, sometimes even the seat belts are found also attached to the seat, thus providing even more convenience to the occupants. In that case however, the seat track design must be configured to withstand thousands of pounds of force should an accident occur.

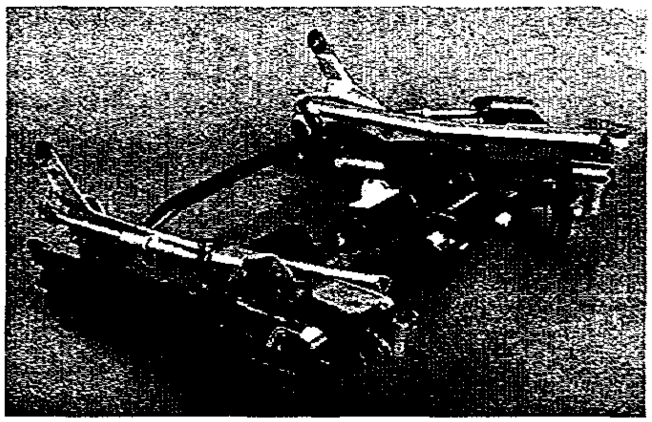

Figure 1: Eight Way Power Seat Adjuster

Figure 1 shows an eight way power seat adjuster that is designed for the attachment of a seat belt buckle on the inboard side of the device. It's considered to be "eight way" due to the bidirectional movement of the horizontal, front vertical, rear vertical and recliner subsystem. In this design, all adjustments are realized by means of motorized lead screws and internally threaded drive nuts. As the motor armature rotates and turns the lead screw, the drive nut traverses the length of the lead screw, and by means of interconnecting linkages, the seat track upper frame members move relative to the seat track lower frame members.

To be more specific, the horizontal motion, or sometimes referred to as fore and aft motion, is achieved by means of a lead screw and a threaded drive nut as shown in Figure 2.

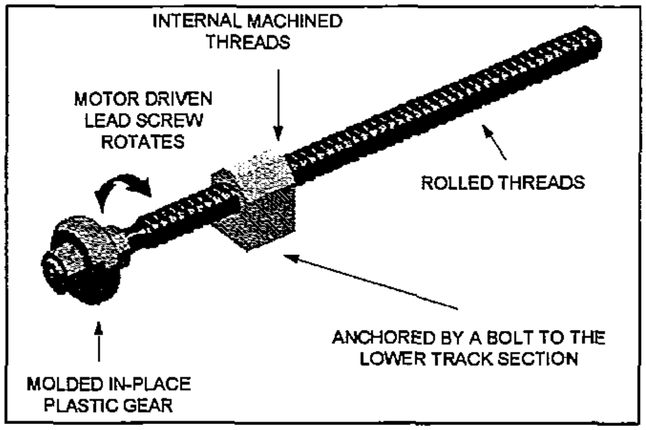

Figure 2: Lead Screw and Drive Nut Subassembly

As the drive motor armature rotates, it drives the lead screw at about 150 RPM by means of a gear set. The pitch on the lead screw thread thereby pushes the lead screw in the rearward direction or pulls the lead screw forward relative to the lower track, and likewise relative to the vehicle floor pan. The horizontal track speed thus depends on the gear ratios, the torque/speed characteristics of the motor and on system loads.

Vertical seat adjustments are derived using a similar control concept both in front and rear of the seat track. For the squeal issue at hand, the horizontal control mechanism is of principle interest but the same type of problem could occur on the vertical adjustment given the right set of resonant conditions.

PROBLEM IDENTIFICATION

The squeal sound was found to come from the mechanical interface between the horizontal lead screw and the steel drive block. The sound was relatively pure and occurred nominally at 480 hertz. The frequency was consistent from unit to unit, but the amplitude varied greatly. Sometimes the noise would disappear if given the right conditions, and on some percentage of seat tracks the noise/vibration did not occur at all. Of significance was the fact that the noise frequency was independent of the motor speed and track speed of movement. In some cases, the noise could be reduced or eliminated by lowering the vertical height adjustment, or by loosening the anchor bolts at the floor attachment points.

It became evident that the squeal was a natural resonant frequency of a subsystem or component, and its presence depended on fixturing and unit loading of the seat track. After accumulating large amounts of data from various experiments, the squeal was found to be created by the lateral forces of the drive nut against the lead screw and the frictional surface at that point. When rotating, the localized sliding of the internal thread of the drive nut triggers the lead screw to begin vibrating at its natural resonant 480 Hz frequency. Squeal begins when the drive nut reaches a node on the vibrating lead screw. The lead screw, when vibrating inside the drive nut, created the 480 hertz squeal sound. Therefore the drive block served both as the excitation means and the reaction surface against which the lead screw vibrated. Test data that confirms this circumstance is shown in the following three figures.

Figure 3 shows the typical acoustical spectrum associated with the squeal noise. When the track sounds off, the occupant's ear can easily pick up the noise and its related set of higher harmonics. These measurements were taken using a fixtured seat track positioned in its upmost vertical position and moving towards the rear. A microphone was used to input the acoustical energy into a spectrum analyzer. When the track reached about 80 millimeters of rearward travel, the sound started and was recorded in Figure 3. The band of excitation begins at about 480 Hz. and extends to beyond 560 Hz. This is because the analyzer samples the sound emanating from the moving seat adjuster for a time slot during which the geometry of the vibrating system changes slightly and thus the up shift in plotted frequency.

Figure 4 shows the typical mechanical energy of the squeal sound. An accelerometer was arranged to monitor the vibration energy while the track was in motion and the motors were running and while the track was squealing. It's clear by comparing the spectrum of Figure 3 to that of Figure 4, that the sound is being created from the track parts vibrating at the same 480 Hz frequency.

A modal analysis of the lead screw was performed while it was still mounted in the seat track and then again while alone as a free body, see Figure 5. For the first case the motors were not energized and the lead screw was not turning. The Quadrature Amplitude test method was used which shows the relative physical displacements of the lead screw as well as the relative phase of the vibrational motion, Reference 1. The lead screw was struck with an impact modal hammer and the measurements were recorded. For this test, the position of the drive block was set about 80 MM from the free end of the lead screw. This corresponds to the same horizontal position that the squeal typically becomes audible as the seat track is moving.

Figure 5 shows that the lead screw assembled in the seat track and struck with the impact hammer vibrates at 482 hertz with a mode shape similar to a free-free mode. One might think that the gear box end of the lead screw is anchored firmly, and should not whip. However, the displacements as shown in this test were relatively small excursions with respect to the allowable lash within the gear box assembly. Consequently the lead screw, when squealing, is actually vibrating in a free-free mode as opposed to a fixed-free mode that was originally thought.

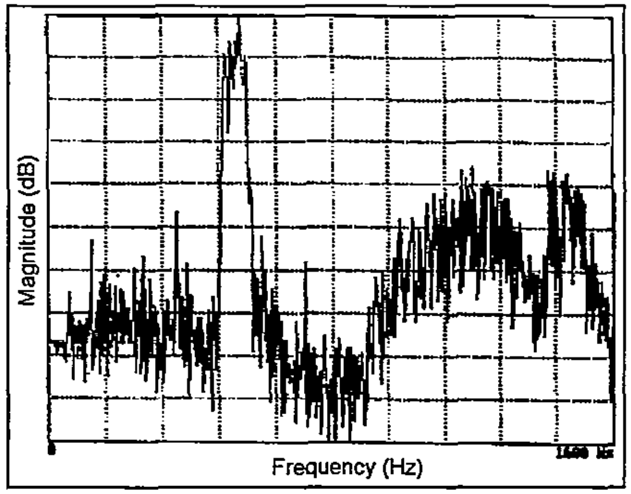

Figure 3: Acoustical Frequency Spectrum, Squeal

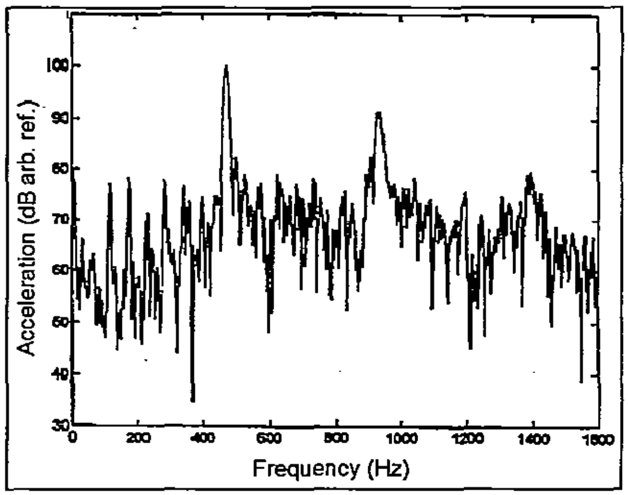

Figure 4: Vibrational Frequency Spectrum, Squeal

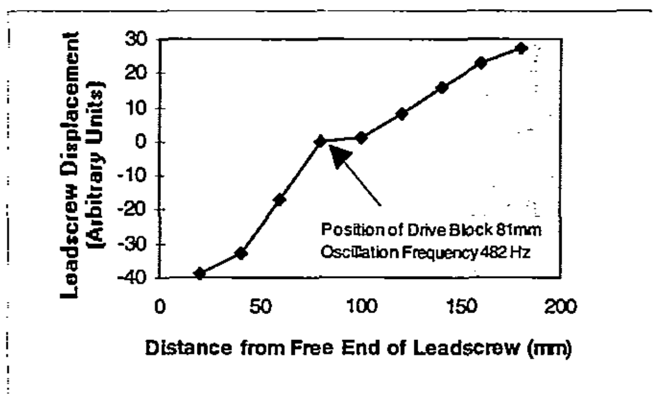

Figure 5: Modal Analysis, Lead Screw in Track Section

As a double check, the lead screw was also analyzed as a free body, and the results showed that it vibrates alone at 490 hertz, which is an excellent confirmation of its behavior in the track assembly.

Hand calculations were used to confirm that the lead screw was vibrating in the Free - Free mode and not in the first cantilever mode. Equation 1 was used to make the assessment, Reference 2.

$$f_1 = [\lambda_1^2 / (2\pi L^2)]^* [EI/m']^{1/2}, \qquad \text{Eqn. 1}$$

$$m' = m / L, \qquad \text{Eqn. 2}$$

$$I = \pi r^4 / 4, \qquad \text{Eqn. 3}$$

Where:
λ_1 = 4.73 for free - free modal vibration
L = length of lead screw, 0.279 meters
m= mass of lead screw, 0.186 kg
E= modulus elasticity, carbon steel, 19.5x1010 N/m
I = moment of inertia about neutral axis
r = lead screw root radius, 4.64mm

By using the measured and material constants of the manufactured lead screw and by substituting Eqn. 2 and Eqn . 3 into Eqn. 1, the calculated resonant frequency is f_1 = 472 Hz which is accurate to within the tolerance of the material constants used. If these same calculations are made but for the fixed - free mode the modal frequency would be 90 Hz.

This finally substantiates the theory that the squeal sound is created by the lead screw vibrating at its first free - free mode natural resonant frequency. The high amplitude excursions of the lead screw strikes the adjacent track parts and moves the surrounding air to produce the squeal sound.

On a practical note, the squeal sound spans over a band of frequencies but near the resonant frequency of the lead screw. Both the manufacturing tolerances of the parts and the fact that they function within a whole set of other parts tends to spread the frequency band.

The Engineering task now is to determine a means, with 100% certainty, to prevent the lead screw from vibrating.

ENGINEERING APPROACHES - SHORT TERM

Most of the ideas to solve the squeal in the short term were an outcome of various brainstorming meetings and a design of experiments. It was suspected at this early stage that the squeal was a result of the frictional variations of the sliding bearing surfaces between the lead screw and the steel drive block, but it was not until later that the root cause of the frequency range of the squeal was linked to the free-free vibration mode of the lead screw. All of the solutions that resulted from the brainstorming and the design of experiments could be classified under three different engineering approaches: *eliminate the excitation force, shift the natural resonant frequency*, or *dampen the resonating components.* These engineering approaches will be examined on their theoretical fundamentals, prototype test results, and application concerns.

ELIMINATE EXCITATION SOURCE - One approach to eliminating the objectionable noise would be to eliminate the wide band vibration which is a result of the frictional variations of the sliding bearing surfaces between the lead screw and the steel drive block. Once the wide band, stick slip vibration was eliminated the lead screw would not resonate. This approach could be accomplished through a variety of methods some of which are as follows: improve the surface finish of the load bearing areas, increase the bearing area to distribute the load by optimizing the alignment, add additional lubricants or coatings to the bearing area, or change the material of either one or both of the bearing areas.

With an improved surface finish of the lead screw threads, internal drive block threads, or both, the coefficient of friction would be reduced, therefore possibly lowering the frictional variations with an end result of reducing or eliminating the squeal. Unfortunately, the repeatability and consistency of the surface finish was never developed to a point of success in removing the squeal. The following is a list of surface finish methods which were *not* successful:

- changing the torx bolt thru-hole in the drive block to a blind hole, thus removing the chance of a burr in the lead screw thru-hole
- polish the internal drive nut threads by tumbling or a Thermo De-burring process
  polish the lead screw threads

The only positive results from the surface finish improvement theory were related to the tapping and orientation procedure of the outside diameter (OD) centralized internal threaded drive block as shown in Figure 6.

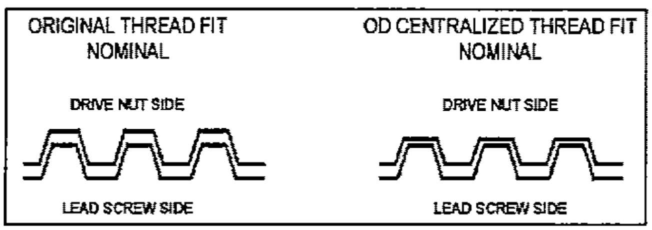

Figure 6: OD Centralized Thread Design Comparison

The OD centralizing approach was to eliminate the excitation by increasing the bearing area between the mating parts and evenly disperse the frictional load. This could be accomplished by optimizing the alignment of the lead screw thread's pitch diameter to the drive block internal thread's pitch diameter, therefore increasing the area of engagement, thus reducing the amount of point contact resulting in lower per unit area friction forces, see Figure 6.

Putting an OD centralized thread in the drive block showed positive results. This short term solution theoretically "tightened" the tolerance between the lead screw and the drive block, therefore "held" the lead screw more rigid which prevented it from resonating. The OD centralized thread drive block and its orientation will be further discussed in the conclusion of the short term solutions.

The other positive alignment solution was the idea of a drive block with a Gimballed joint. The concern with addressing the alignment problem was that the amount of mis-alignment could change while operating the seat track and as components would wear during the life of the assembly. Therefore a design was needed which was insensitive to the changes in mis-alignment. The Gimballed joint would add two degrees of freedom to the system, thus allowing the lead screw and drive block to align itself through the length of travel without restricting either component in any way, see Figure 7. The Gimballed Drive Block will be further discussed in the long term solutions.

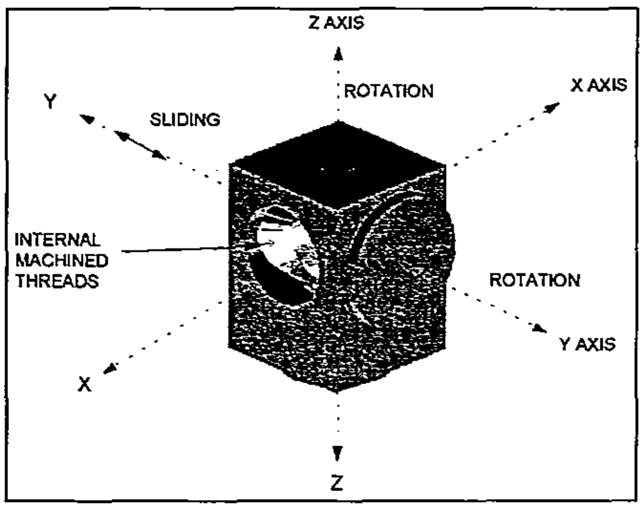

Figure 7: Gimballed Joint Horizontal Drive Block

One of the first things an engineer thinks of when trying to solve a friction based problem is the use of lubrication. Lubrication can be a very critical design constraint dependent on the type, amount, application process, etc., but the most robust designs are not dependent on such constraining requirements. Although there were speculations of how durable each method might be and how effective the lubricant method would be in removing the squeal the following trials were completed with *no* significant improvement over the life of the assembly:

- oil impregnated brass drive blocks
- synthetic lubricant on the drive block threads
- dry film lubricant on the drive block threads and lead screw threads

The manufacturing engineers also investigated the amount and process of applying the current lubricant to the lead screw threads in a more consistent method. Although the process and amount of lubricant was optimized, the final product had no significant improvement when tested for the squeal condition.

The final method to eliminate the squeal noise by eliminating the excitation source was to alter the steel on steel interface by changing the drive block material. Three iterations of this method retained the metallic interface but were not 100% successful in removing the squeal. The metallic blocks consisted of oil impregnated brass, meehanite, and bearing bronze. The other approach was to incorporate plastic, either as the entire block or just an insert molded thread in a steel block. The reason plastic was not initially used on the load bearing side of the assembly, as a plastic block is used on the non-load bearing side, was because of the Federal and customer requirements for seat track structural strength. Although this was the case, a high tensile plastic drive block or a plastic insert molded steel drive block could be designed to withstand the structural requirements and remove the frictional variations found in the drive block and lead screw interface. With initial positive results for the plastic insert molded drive block, further design iterations were carried out and the results will be further discussed in the long term solutions.

SHIFT NATURAL RESONANT FREQUENCY - As stated previously, the root cause of the squeal noise was that the lead screw's natural frequency of approximately 482 hertz was excited by a wide band vibrational excitation caused by the microscopic friction variations between the lead screw and the drive block. If the lead screw did not resonate, then the only audible noise from this area of the drive mechanism would be directly from the mechanical interface between the lead screw and drive block. Although this noise was not of the same amplitude as the squeal, it was considered objectionable by some listeners and was referred to as a "ghost" squeal.

One theory to eliminate the squeal would be to shift the natural frequency of the lead screw out of the wide band excitation vibration. In this case the lead screw would no longer resonate, and the squeal would reduce to a "ghost" squeal or disappear entirely. Although the idea was theoretically correct, it was difficult to alter the natural frequency of the lead screw without a redesign of the horizontal drive system. Therefore only minor changes could be made to the lead screw design, and these were not enough of a change to eliminate the squeal.

Another approach would be to alter the dynamics of the lead screw, so that it would not resonate in the free-free state, but in a fixed-free state. This was accomplished using a plastic bearing (snubber) which was attached to the upper track section at the end of the lead screw, see Figure 8.

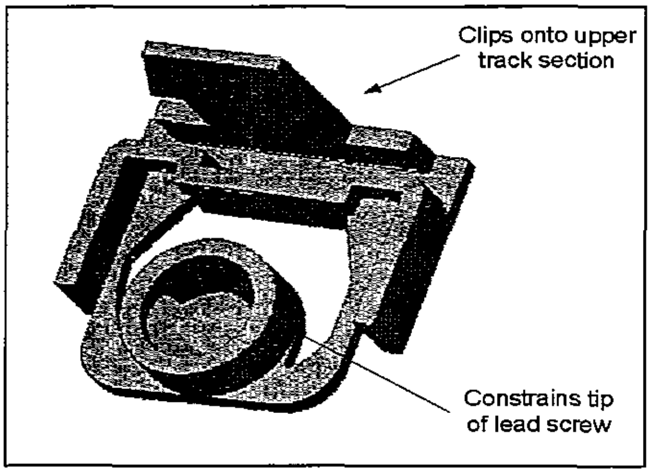

Figure 8: Plastic Lead Screw Tip Bearing, "Snubber"

The tip of the lead screw would be constrained in the plastic bearing (snubber). The theory was that if the tip of the lead screw was not able to "whip", then the lead screw would not resonate in the same mode, therefore possibly reducing or eliminating the squeal. Two different versions of a snubber were prototyped and tested with some success. Unfortunately, the final design of the snubber was not easily installed, and did not remove the squeal 100% of the time under all circumstances.

DAMPEN THE RESONATING COMPONENT(S) - The final approach to solve the squeal issue was to dampen the resonating frequency range which would reduce the amplitude of vibration and inherently reduce the audibility of the squeal. There were two methods explored along this approach. One could dampen the amount of vibration of either the drive block or the lead screw. The latter method seemed to be more effective, because the damping element could be more strategically placed.

The drive block, by design, was able to rotate about the Z-axis on the lower track due to the shoulder height of the drive block and thickness of the upper track, see Figure 9. The theory behind dampening the drive block was that the looseness in the system allowed the drive block to resonate against the lower track and produce air borne noise, and if this resonance was dampened the air borne noise would be eliminated.

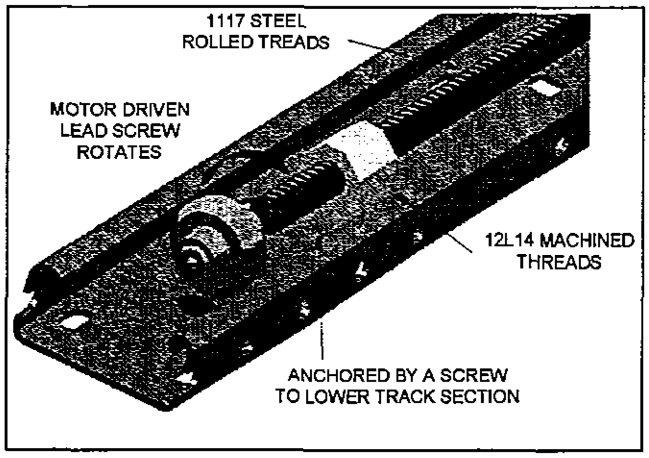

Figure 9: Lead Screw, Drive Block & Track Section

As a short term solution, two different methods were used to dampen the drive block. A Mylar washer was placed between the drive block and the top of the lower track. This solution had little to no significant affect on eliminating the squeal. As an alternate solution for the squeal, a viscoelastic polymer material between the drive block and the top of the lower track was also tried. Although this solution seemed to eliminate the squeal, further testing and manufacturing issues proved it was not a statistically viable solution for production.

The second method would be to apply dampening to the lead screw. As stated previously, the lead screw was vibrating in a free-free state with the free end of the lead screw having the largest displacement, see Figure 5. Therefore, if a mass-spring damper having the same natural frequency as the resonant frequency were added to the end of the lead screw, its out-of-phase motion with the lead screw motion would eliminate the ability of the lead screw to vibrate. Consequently with the displacement of the lead screw minimized, the audible squeal sound was eliminated.

As a further experiment towards a complete understanding of the dynamics of the problem, a dense mass was attached to the free tip of the lead screw. The weight acted to mass dampen the vibration of the lead screw, and it was partially successful. As a better understanding of the squeal properties was developed, a mass-spring damper was designed. Through many different iterations to improve the robustness of the mass-spring damper, it was 85 to 100% successful in removing the squeal. Because the mass-spring damper could be easily installed on the tip of the lead screw and would require minimal durability or environmental testing, the mass-spring damper was one of the three parallel paths taken to solve the squeal issue, and will be further discussed in the long term solutions.

CONCLUSION: SHORT TERM SOLUTIONS - After examining the possible methods of solving the squeal issue in each of the three engineering approaches, it was decided to implement the "best" short term solution and continue investigation and testing of three promising designs.

The OD centralized steel drive block was implemented into production along with 100% end-of-line containment testing. This short term solution addressed the root cause of the squeal problem by eliminating the excitation source because of its better surface finish on the internal threads, improved alignment of the lead screw, and its ability to constrain the lateral motion of the lead screw. The improved surface finish was a result of a combination effort to develop a more precise, and repeatable tapping procedure which monitored tool wear and added extra tapping operations. The drive block was also oriented during assembly to position the tap entry side of the drive block to face the horizontal gearbox, thus the lead screw would enter the drive block in the same side as the tap.

Besides the implementation of the OD centralized drive block, there were three other design solutions which were pursued as long term solutions, because of their ability to remove the squeal 100% of the time and also because the reasoning used to describe why they were successful was theoretically sound. These three solutions were as follows and will be further discussed in the long term solution: *mass-spring damper, plastic insert molded drive block*, and the *Gimballed joint drive block*.

ENGINEERING SOLUTIONS - LONG TERM

As the short term solutions were discarded for not eliminating the squeal and a better understanding of the root cause was generated, three designs were followed as possible long term solutions. In order to classify a design as a long term, viable engineering solution to the "squeal" problem, the design had to have the following characteristics:

- manufacturability
- minimum cost impact
- eliminate the squeal 100%

Although a solution might fall within the long term solution category, it could still be classified as a "band-aid" approach, because it did not address the fundamental physical phenomenon of the squeal. The following describes the theory, design iterations, engineering or manufacturing issues, and the production feasibility of the three long term parallel path solutions.

MASS-SPRING DAMPER - The theory to use a mass-spring damper to solve the squeal was a derivative of the tuned damper used to solve machine tool chatter. Self-excited machine tool chatter has been described as an unstable interaction between the cutting process and the machine tool structure, Reference 3. The closed loop process of how the cutting force to the cutting depth depends on the machine tool deformation and visa versa can be compared to the lead screw and drive block interaction. The side loading of the drive block caused by the mis-alignment of the lead screw must balance the output force of the drive block, otherwise the system will begin to chatter. As stated in the Problem Identification section, this chatter was determined to be the root cause of the resonating lead screw. Therefore, if the side loading forces were balanced and the loop was stable, the chatter would be eliminated, the lead screw would not resonate, and the squeal would be eliminated.

If the machine tool chatter application was directly related to the lead screw drive block interaction, the mass-spring damper would be placed on the drive block to stabilize the side loading caused by mis-alignment. Unfortunately, the design constraints of the application forced an alternative location for the mass-spring damper. Instead of balancing the closed loop interaction of the drive block and lead screw, the damper was placed on the tip of the lead screw to counteract the lead screw displacement as it began to resonate. The general theory behind using a mass-spring damper in this application was that if the damper had the same natural frequency as the resonant frequency (squeal frequency), its out-of-phase motion would significantly reduce the amount of lead screw displacement. With the damper installed, the lead screw was operating in its static equilibrium position which created a stable closed loop system and the tendency for an audible squeal was eliminated.

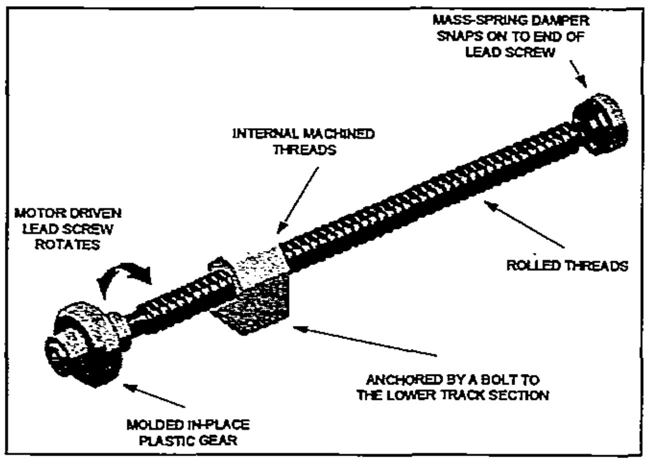

Figure 10: Mass-Spring Damper, Installed

The mechanical properties of the mass-spring damper were designed from basic equations for spring rate, and natural frequency, Reference 3. The damper consisted of a concentrated mass suspended off the end of the lead screw by a retaining clip and a piece of rubber, see Figure 10. The rubber which was attached to both the retaining clip and the mass acted as a spring in shear, therefore the linear spring rate and natural frequency were calculated using the following equations:

$$k = AG/h \qquad \text{Eqn. 4}$$

$$f = \frac{1}{2} (k/m)^{1/2} \qquad \text{Eqn. 5}$$

Where:
- A = cross-sectional area of the rubber in meters^2
- G = shear modulus of the material in Pascals (≈1/3 Young's modulus for rubber)
- h = thickness of the rubber in meters
- m = mass in kilograms

A couple of concerns arose during the validation testing of the mass-spring damper. Although the damper proved to be effective on most seat track assemblies, after the implementation of the OD centralized drive block, there were a few cases where a "ghost" squeal was still audible with the tuned damper installed. As the mass-spring damper's effective frequency band was enlarged to cover all known squeals, its ability to significantly reduce the amplitude of excitation decreased.

Although the standard drive block could have been re-released with the tuned damper as a long term solution, the method to attach the damper to the lead screw was another manufacturing and design concern. In order for the damper to work properly, it had to be attached to the lead screw symmetrically and securely, so that the rubber material was working in shear between the attachment clip and mass, and so the tuned damper would remain attached during the life of the seat track assembly, see Figure 11.

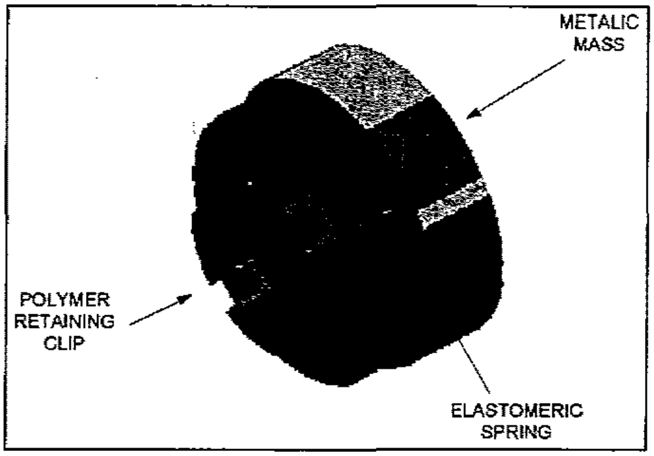

Figure 11: Mass-Spring Damper - 3D Model

The biggest concern with the mass-spring damper was its inability to solve the "squeal" problem by addressing the root cause. Although the damper proved to be effective on all but the OD centralized drive blocks, the design did not address the root cause of the squeal. The mass-spring damper when installed did not prevent the high side loading of the threads, or prevent the lead screw and drive block interaction from a stick-slip condition, it only reduced the amplitude of displacement of the lead screw once the stick-slip phenomenon caused the lead screw to resonate. This concern, along with the manufacturablity issues, caused the mass-spring damper design to be classified as a "band-aid" fix, and therefore was not pursued as a production solution.

PLASTIC INSERT MOLDED STEEL DRIVE BLOCK - The plastic insert molded steel drive block was developed with the idea that the squeal associated with the steel to steel, drive block to lead screw, interface in the power seat adjuster would be eliminated by using a plastic to steel, drive block to lead screw, interface. The theory was based on the fact that plastic provides a lower coefficient of friction, smoother bearing surface, and dampens vibration. Although this solution would not disperse the side loading caused by the mis-aligned lead screw, it would eliminate the lead screw from resonating. The "ghost" sound attributed to the stick-slip steel to steel interface would also be eliminated. Even though the plastic insert molded steel drive block did not directly address the root cause, it was able to eliminate both the typical squeal and the "ghost" squeal.

The initial design of the plastic insert molded drive block was developed and tested. The first prototypes consisted of a steel cage slightly larger than the current steel block, with a M18x1.5 thread machined through the body to retain the plastic slug, a M10 thread machined through the base for retention to the lower track, a drilled hole through the top to allow for the gate, and a plastic slug injection molded in the cavity, see Figure 12. Three materials were strength tested on a tensile test machine to determine a plastic for this application. The 40% long glass fiber reinforced Nylon 66 was chosen for its higher tensile loads.

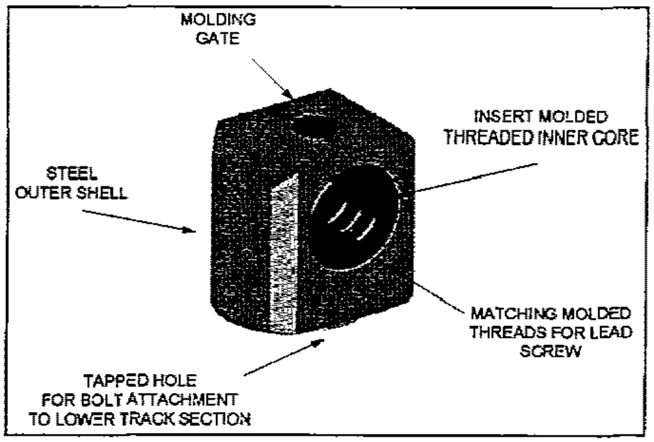

Figure 12: Plastic Insert Molded Steel Drive Block

Once a material was chosen and the cage design was finalized, further testing was completed to validate the design. A modified life test was designed to validate the wear and strength properties of the drive block after a simulated life. Two assemblies were validated per the modified life test, and anchorage tested following the successful life cycles. After the ambient anchorage tests, a modified anchorage test was designed to validate the strength of the assembly at elevated temperatures. Initially a correlation from the tensile test machine to the seat track anchorage test was attempted, but because of the mis-alignment of the lead screw which was exaggerated during an anchorage test due to the off-set load path, a correlation could not be found. Following the failure of the first elevated temperature tensile test, a matrix of various plastics was assembled and a test plan was implemented, see Table 1. Although the plastic insert molded steel drive block was successful in eliminating the squeal 100% and passed all typical design validation testing, a plastic was not found that would withstand the elevated temperature seat track anchorage test.

Material	Tensile Test Ambient	Tensile Test (65°C)	Anchorage Test (65°C)
Steel	NA	NA	5249#
Nylon 66, 40% Glass	4717#	2890#	2684#
Nylon 66, 50% Glass	NA	NA	3029#
Nylon 66, 60% Glass	5004#	3618#	NA
Nylon 66, 40% Carbon	NA	NA	3068#
Nylon 46, 40% Glass	5117#	4327#	3100#
Nylon 46, 50% Glass	4875#	4439#	3036#

Table 1: Alternative Plastic Material Test Matrix

After brainstorming with plastic experts, multiple design iterations, and extensive testing, the insert molded plastic drive block failed to meet the high temperature safety requirements. Although the tensile tests prove the plastic block can withstand the required load in a straight pull at high temperature, the current design of the track did not allow the lead screw drive block assembly to replicate a tensile pull during an anchorage test or a vehicle crash situation. It has been observed that the drive block tips forward during an anchorage test which mis-aligns the lead screw with respect to the internal threads of the drive block. The second observation was that the first failure mode during an anchorage test forces the rear of the lead screw down to the lower track, and drastically mis-aligns the lead screw with respect to the internal threads of the drive block. These two mis-alignments of the horizontal drive sub-assembly reduce the amount of surface area contact and pure shear of the plastic threads, therefore reducing the load the internal plastic threads of the drive block can withstand. In order to further pursue any drive block with load bearing plastic threads, a redesign of the cage and / or track assembly needs to consider this mis-alignment.

GIMBALLED JOINT DRIVE BLOCK - In order to develop a solution which would fall within the long term category and address the root cause of the squeal, the mis-alignment of the lead screw to the internal threads of the drive block must be eliminated. By improving the alignment of the horizontal drive, the likelihood that the stick-slip phenomenon would occur will decrease, therefore the squeal which was a result of the lead screw resonating due to the vibration caused by the stick-slip motion would decrease as well. It was hypothesized that if the alignment were self-adjusting then the stick-slip phenomenon would be eliminated, which in theoretical terms would be equivalent to breaking the feed back loop of the reaction force, and the squeal could no longer exist. One method to achieve this self-aligning feature would be to add the necessary degrees of freedom to the drive block.

An idea that stemmed from the sailing industry was to add a gimballed joint to the drive block. Similar to the two-degree-of-freedom gyroscope used to suspend a ship's compass in the horizontal frame regardless of any rocking motion of the boat, a gimballed drive block was developed to allow the lead screw to self-align regardless of any location of the horizontal gearbox, see Figure 13. As shown previously, the final design of the gimballed drive block has three degrees of freedom which are as follows: rotation about the Z-axis, rotation about the Y-axis, and sliding along the Y-axis, see Figure 7. These three degrees of freedom allow the internal drive nut threads to align with any orientation of the horizontal gearbox, therefore eliminating the side loading present with the single-degree-of-freedom drive block.

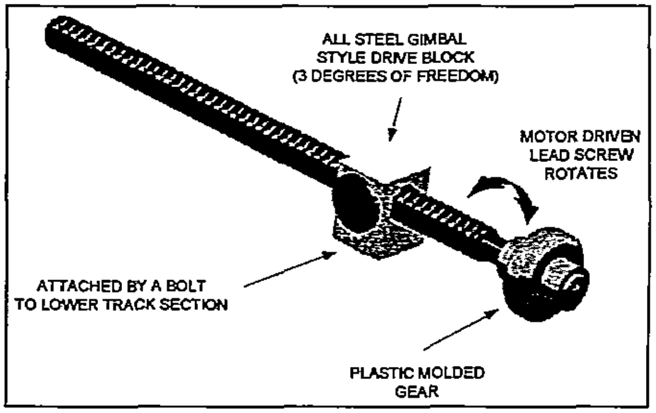

Figure 13: Lead Screw with Gimballed Drive Nut

Although this design utilized basic concepts, in order to manufacture the drive block without introducing new customer issues, the supplier had to be a part of the final design. The early supplier involvement in the design process was to insure the cylindrical nut would always have free rotation independent of the environment and have a snug fit to minimize the risk of a buzz, squeak and rattle issue or a fore-aft chuck, "horizontal stability", issue. By allowing the supplier to finalize the dimensions, they were able to decrease the amount of tolerance and minimize the variation between parts.

Following successful design validation testing and necessary due care tests, the gimballed drive block was implemented into current production. The required performance, durability, extreme temperature, and structural testing was completed per the customer test standards with no open issues or failures. Following the typical validation tests, a corrosion test, thermal/humidity test, noise and vibrations tests, and vertical and lateral misalignment tests were completed. The intent of the due care tests was to insure that the cylindrical nut did not seize up under any extraneous vehicle environment, and to verify that the design intent amount of allowable mis-alignment was sufficient for the application environment. Once the robustness of the gimballed block design was validated, the block was implemented into production.

CONCLUSION

The automotive design engineer when working with lead screw configurations can benefit from the lessons learned from this experience. First when dealing with noises categorized as natural resonant frequencies, the greatest amount of understanding will come from a detailed modal analysis, rather than a heuristic approach. Secondly, once the vibration modes are understood, alternative solutions which address these modes will become evident, and they can be explored. More over, when dealing with frictional interfaces, the designer needs to be aware of such feed back forces that can be relieved through additional degrees of freedom.

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