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Sound Quality Assessment of Powered Seat Adjusters

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ABSTRACT

With the extensive improvements achieved in vehicle driveline and road noise quality manufacturers are turning their attention to component and ancillary noise sources and expecting their suppliers to include sound quality in the assessment of their designs. This paper describes an investigative project into the principal components contributing to the perceived sound quality of powered seat adjusters in passenger vehicles and the statistical methods of analyzing jury preference data.

INTRODUCTION

Over the last ten years significant advances have been made in relating the subjective perception of vehicle sound to objective measures or metrics.

Most of this research has been directed towards powertrain and road noise, the individual characteristics of these sounds and a suitable balance between them. As the technology advances manufacturers are realizing that the perception of sound quality involves an overall impression of the vehicle rather than concentration on any given component.

Sound from discrete events, such as door and trunk closing, and electrically driven components (wiper motors, starter motors, seat adjusters etc.) can add or detract from the perceived quality of the vehicle.

As with driveline sound the total absence of sound is not necessarily the requirement. Drivers often need feedback that "something is happening" and while a total absence of wiper noise might be the ultimate solution it may be economically unattainable.

In considering a particular sound quality problem consideration must also be given to the masking effect of other sounds in the environment in which the device will be normally operated. Wipers will normally be operated only with the engine running while an electric radio antenna will still be retracting after the engine has been turned off.

Seat adjusters are normally operated when the driver first enters the vehicle, particularly if the seat is a long way out of adjustment. This represents the worst case as there are no other sources to provide masking of the adjuster noise.

When working on new designs for power seat adjusters, a number of criteria need to be addressed in addition to the quality of the power mechanism sound. The discriminating consumer also demands greater travel lengths, improved ride quality (smoothness of operation), and stability (track looseness exhibited while braking and/or accelerating). From an OEM's perspective safety, weight, and, of course, unit cost, add additional design challenges. Current production adjuster did not adequately address all of the aforementioned subjective characteristics.

Centered around a rack and pinion type design (Figure 1), the system did not provide a "smooth ride" and was susceptible to slight movements during acceleration and braking (Known as "chuck" or "stability").

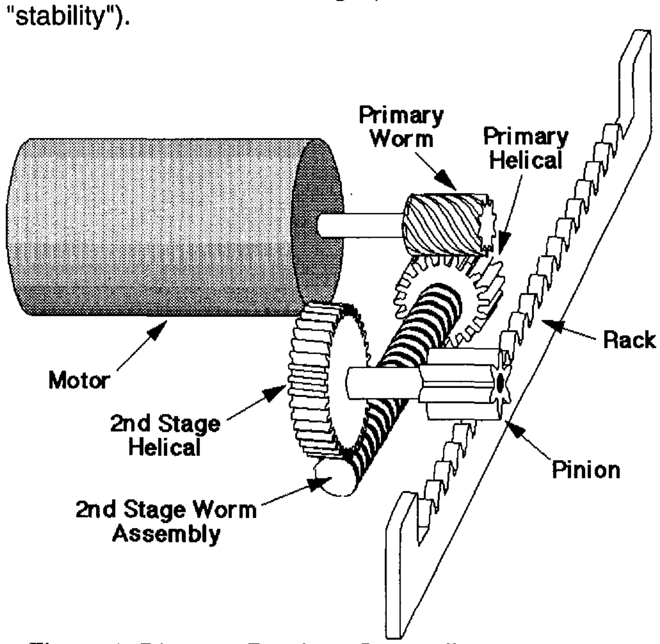

Figure 1. Diagram Previous Seat Adjuster Mechanism

Finally, although quiet in terms of decibels, the rack and pinion system did not lend itself to a quality sound signature. The periodic impacting of the pinion to the rack often generated an impulsive "tick" found objectionable by the consumer. This same "ticking" produced a vibration input to the occupant resulting in a "rough" ride.

The aim in design of the new adjuster focused on both the objective and subjective qualities dictated by the customer. A preliminary study found that a simplified design using a screw/nut drive system (Figure 2) would provide superior stability, smoothness of operation, and flexibility for incorporation into other car models.

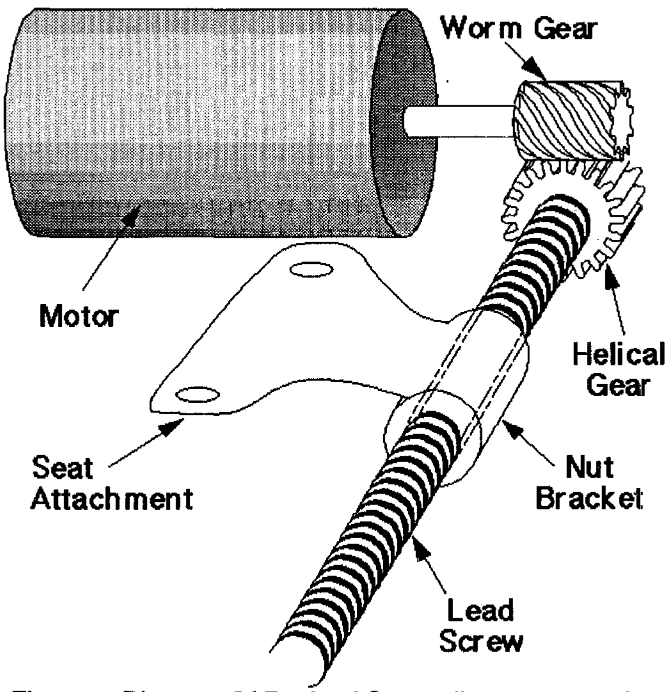

Figure 2. Diagram Of Revised Seat Adjuster Mechanism

One major issue to address would be quality of the sound developed by the mechanism. There was no database of experience regarding the acoustics of a screw/nut drive system within the company. Therefore, once prototype seat adjusters, incorporating the screw drive system, had been built they were tested against the existing production rack and pinion design as well as competitor's designs.

SOUND RECORDING

Seven seat adjusters were chosen as representing a wide variety of mechanisms from different manufacturers.

The recordings were made with the seats fitted in the appropriate vehicles. A 90kg. mass was placed on the seat for correct loading and a binaural head and torso simulator was placed on top of the weights.

A current shunt device was attached to the motor power supply and this produced a conditioned output that was used as a motor tachometer signal.

To prevent test variations due to battery voltage degradation the seats were powered by a 20amp DC power supply.

Binaural sound and tachometer signals were recorded onto DAT tape for analysis.

The seat adjusters were recorded under all operating modes (forward-backward, up-down, lumbar in out etc.) over the full range of adjustment. For simplicity only the analyses of the forward adjustment are presented in this paper.

DATA SIGNAL PROCESSING

Many metrics have been developed to allow numerical evaluation of sound quality. Not all of these metrics will have significant correlation to subjective evaluation of a given sound.

To reduce the number of possible parameters that determine seat adjuster sound quality it is first prudent to understand the individual structures in the sound.

A seat adjuster "event" consists of three sections. Figure 3 shows the sound time history for a complete seat adjustment.

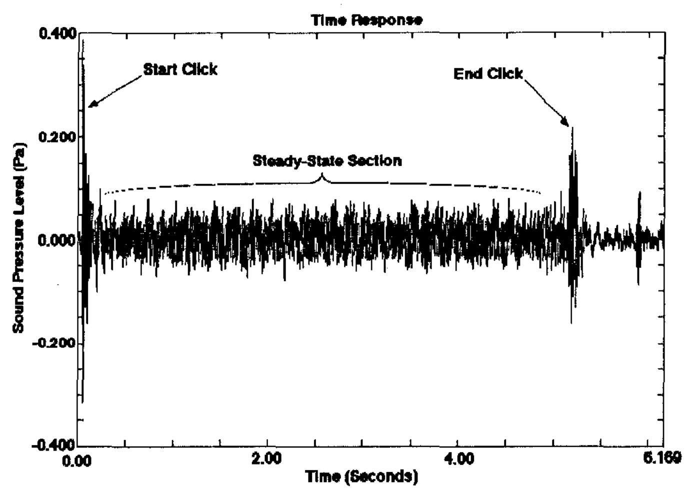

Figure 3. Sound Pressure Waveform Of Adjuster Event

At the beginning and end are transients corresponding with the start-stop of the mechanism. The analysis concentrated on the center, nominally steady-state, section.

Examination of a narrow-band FFT of the time data for the steady-state section (figure 4) shows that the majority of the sound power is below 500Hz, however there are also peaks in the sound power in the 2kHz to 6kHz range.

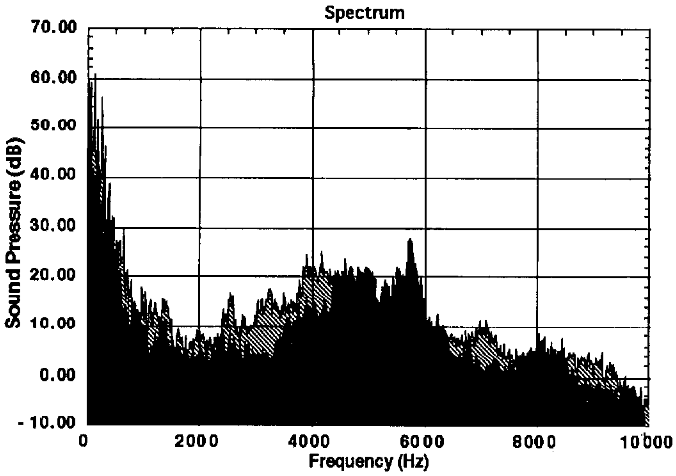

Figure 4. Narrow-band FFT's Of "Steady-State" Sections of Two Sounds

These peaks are significant despite being 30-40dB lower in amplitude than the lower frequency range because of the frequency discrimination of the human ear.

The center frequency, amplitude and width of this peak varies between the different components but it is present in all samples.

Further analysis showed these frequencies to be meshing harmonics of the reduction gear set, in the range of 100 to 200 times motor rotation speed.

This frequency range corresponds to a region that is important in the calculation of such metrics as Intelligibility[1] and Speech Interference Level[2] and is often referred to as the "speech band", that is the 500Hz, 1kHz, 2kHz and 4kHz octave bands.

FREQUENCY MODULATION

A second feature of the seat adjuster sounds is their time dependent characteristics. Although nominally running at a constant speed some of the mechanisms show significant variation with time. Figure 5 compares the RPM vs. time function of three adjusters.

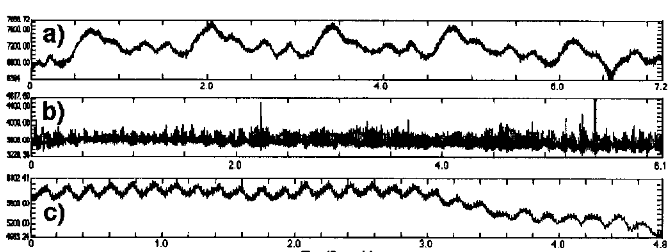

Figure 5. RPM vs. Time Functions From Three Adjusters

The adjuster in figure 5a displays a large, low frequency modulation, at a frequency of approximately 1.5Hz. Figure 5c also shows modulation but at a higher frequency of 6Hz . Figure 5b shows no low frequency modulation but significant levels of high frequency modulation at 56Hz.

Speed variation in the motor gives rise to frequency modulation of the mechanism harmonics. Figure 6 shows a waterfall diagram of a mechanism harmonic at approximately 5800Hz.

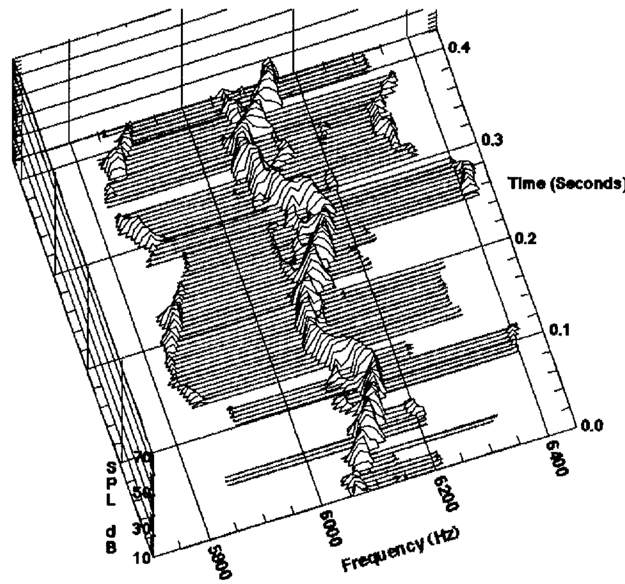

Figure 6. Narrow-band Waterfall Display Showing Frequncy Modulation Of A Gear Mesh Harmonic

This effect explains the broad peak in the sound power seen in the averaged spectra which are actually discrete harmonics modulated in frequency.

The modulation frequencies exhibited by the mechanisms coincide with two psycho acoustic phenomena referred to as Fluctuation Strength[3] and Roughness[4]. These terms describe a sensitivity of human hearing to modulations centered around 4Hz and 70Hz respectively. The modulation can be either in the amplitude or frequency of the waveform to produce the effect.

The low frequency modulation is caused by non-uniformity's in the screw drive causing a variation in the load during one rotation. The high frequency modulation is caused by variations in the load applied to the motor at each tooth in the reduction gear.

In addition to the modulation of the motor speed figure 5 also shows that some of the adjusters have a significant change in speed with position on the track while others maintain a relatively constant speed with position.

This speeding-up or slowing down can be interpreted as a subjective feeling of "weakness" about the motor.

METRIC ANALYSIS

Each of the measured sounds were evaluated for 25 metrics. Examination of the results showed that the range of values for some of the metrics was not very broad. In order to increase the range four new sounds were created by modifying the existing sounds to accentuate certain characteristics. Four new sounds were created to add to the measured data.

Figure 7 shows the filter applied to reduce one of the peaks in the speech frequency bands in one of the sounds.

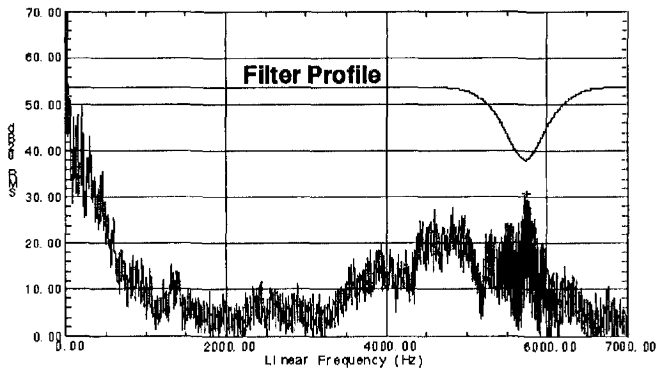

Figure 7. Filter Application To Modify Sound

Other modifications were used to increase or decrease loudness, sharpness and FM fluctuation.

JURY TESTING

Before the sound could be used for jury evaluation the steady-state section of the sounds were edited to make all the files of uniform length to eliminate this variable from the analysis.

The paired comparison technique was used for the evaluation in which the sounds are presented to the jurors in all possible combinations of pairs (55 pairs for 11 sounds) and the juror is asked to register which of the pair is preferable.

The sounds were auditioned using free-field headphones connected with a sound quality workstation with the juror selecting the sound by means of a joystick. The choices were registered by the computer into data files which were used as input to the statistical analysis program.

THE STATISTICS OF THE PREFERENCE

The main object of this work was to identify a model which represented, with a reasonable degree of approximation, the preference for a certain operating mode of seat adjusters.

This basically means identifying the relationship between the objective data, represented by the set of metrics computed for each sound, and the subjective data, the preference scores resulting from the jury evaluation.

This is a problem typically approached by using statistical tools: the general problem is to study the relation between a dependent variable (the preference) and one or more independent variables (the sound quality metrics).

Among the available statistical tools, Regression Analysis is certainly the most commonly used and, to a certain extent, also the easiest to apply. It can be applied only to quantitative variables and it requires making an initial assumption about the nature of the statistical relationship between the dependent variable and the one or more independent variables[5].

As regards the typology of the variables involved in this case, the results of the jury testing (qualitative data) had been transformed into quantitative data by using the following simple logic [6]:

if sound A is better than B, A = +1, B = -1
if A is same as B, A = B = 0.

Regression Results For Two Series Of Data y=0.4434L1 - 0.8026M1 - 0.5534I1 - 28.4931						
Adjuster Number	Pref #1	Rank	Pref #2	Rank	Pred. Pref	Pred. Rank
1	7.95	1	5.59	2	6.81	1
2			5.85	1	6.81	2
3	5.81	2	5.24	3	6.02	3
4	2.30	3	4.10	4	2.38	4
5	1.84	5			2.07	5
6	0.89	6	3.24	5	1.53	6
7	2.00	4	-0.61	6	1.50	7
8	-3.10	9	-3.37	8	-0.84	8
9	-0.29	7	-1.29	7	-1.41	9
10	-1.92	8	-4.24	9	-2.01	10
11	-7.05	10	-4.71	10	-6.88	11
12	-8.45	11	-9.80	11	-9.20	12

Table 1 . Comparison Between Regression Results And Recorded Preferences

Regression analysis was therefore performed on the data and the Analysis of Variance approach was used to test the regression hypotheses and the goodness of the fit.

As is well known, the construction of a regression model requires:

- to define the scope of the model and, therefore, its range of validity; in our case, the sound quality of horizontal forward movements of seat adjusters;

- to select the set of independent variables; it was elected to go for a mixed approach, in which the search of the "good set" of independent variables was based both on specific statistical methods (like all-possible-regressions and automatic search techniques) and on the knowledge of the characteristics of the noise under investigation. The qualitative features of the seat adjusters noise led to the assumption that the model should contain sound quality metrics representative of modulation (due to motor speed variation), impulsiveness (due to the start and stop "clicks" and tooth impact), significant energy distributed along a wide frequency range.

- <u>to choose the functional form of the regression equation</u>; a linear regression model was assumed of the following form:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_1 X_{i2} + ... + \beta_{p-1} X_{ip-1}$$

where Y_i, X_{ij} and β_l are the preference, the set of j variables for the i-th seat adjuster and the coefficients β_l are the regression coefficients respectively.

A well established preliminary approach to testing the goodness of the fit is by using the correlation coefficient, r. It should be noted, though, that the correlation coefficient only measures the "degree of linear association" between the dependent variable Y and the set of independent variables X. There is no single measure that can capture the essential information as to whether a given regression model is the most appropriate for the specific application . In order to truly verify the regression model, other parameters and coefficients have to be computed and evaluated along with the correlation coefficient, as illustrated in the next paragraph.

THE ANALYSIS OF THE EXPERIMENTAL DATA

Since the number of potential variables was relatively high (25 metrics were computed for each sound) and, also, the qualitative features of these sounds gave strong indications about the typology of the dominant variables, the statistical analysis was carried out according to the following procedures:

1) <u>Step-wise regression</u>- A 1st order regression model was computed for each of the p-1 potential independent variables X. The results were simply evaluated in terms of correlation coefficient and typology of the variable, therefore the variables with higher correlation coefficients from each of the three groups of dominant metrics were identified and a multiple regression model, with the set of identified variables, was then formulated.

The result of this first step was a model with 6 independent variables:

$$Y = 0.50L_1 - 0.71M_1 - 0.34I_1 - 0.34I_2 - 5.80M_2 - 0.04M_3 - 32.70$$

being L_1 a "loudness-related" metrics, M_1, M_2, M_3 "modulation-related" metrics and I_1, I_2 "impulsiveness-related" metrics.

2) <u>Searching for the best fit</u>- The previous regression equation still did not provide the best fit, but only the indication of the more meaningful metrics.

In particular, one could argue whether the presence of three "modulation-related" and two "impulsiveness-related" metrics is strictly necessary, in other words if the metrics included in the model and belonging to the same group are truly independent. This is a problem well known in statistics and is generally called intercorrelation or multicollinearity: this phenomena cannot be revealed by the correlation coefficient because the fact that some or all of the X variables are, indeed, correlated does not inhibit the ability to obtain a good fit. This is one of the reasons for which the correlation coefficient alone is not enough for testing the goodness-of-fit of a regression model.

Therefore, in order to find a good model for our application, the set of 6 sound quality metrics, identified in the first part of the project as the independent variables of our model, were tested according to the following criteria (see ref. 5 for definitions):

- the adjusted coefficient of multiple determination, which also takes into account the number of independent variables used in the model;

- the overall F test, for testing the hypothesis of existence of a regression relation between the set of independent variables X and the observed Y by comparing the variation of the Y observations around the regression line to the variability of the Y's associated to the regression line;

- the t* statistics for each regression coefficient, frequently performed together with the overall F test to detect any intercorrelation between X variables;

- the Analysis of Variance approach, based on the partitioning of sums of squares and degrees of freedom associated with the response variable Y.

THE RESULTS OF THE ANALYSIS

The criteria described in the previous paragraph were all applied to the set of six variables contained in the first model to identify the best regression equation, that is the one which provides the best fit with the minimum number of linear independent variables.

The resulting regression equation contains only three variables:

$$Y = 0.4434L_1 - 0.8026M_1 - 0.5534I_2 - 28.4931$$

one for each of the three groups of sound quality metrics.

Table 1 presents, for the population of seat adjusters measured (column 1), the actual preferences derived from the first jury testing and the associated ranking (cols. 2 and 3), the same data for a second jury round (in which one seat adjuster was added and one removed, cols. 4 and 5), the predicted preference (according to the final regression model) and the associated ranking. Fig. 8 shows the comparison between the predicted and the measured preferences for both sets of data (corresponding to the two jury evaluations).

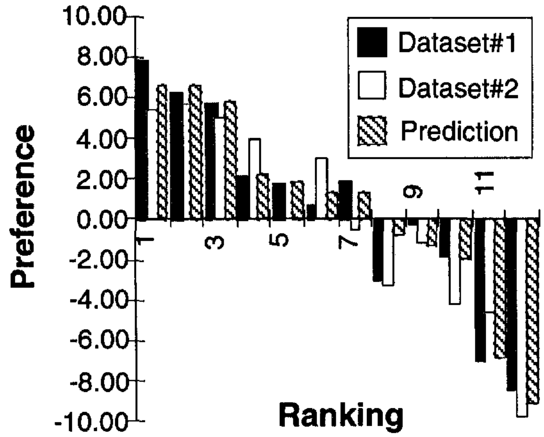

Figure 8. Graph Of Measured and Predicted Preferences For Auditioned Sounds

The intermediate results which led to the assessment of the final model are also of some interest:

- the analysis of the correlation coefficient, of the adjusted correlation coefficient, the overall F* test and the t* statistics, left little doubt about the importance of L_1 and M_1 respectively as X_1 and X_2;

- a third variable, to be identified among I_1, I_2 and M_2, would have improved the model;

- the qualitative features of the seat adjuster noise strongly suggested the third variable being either I_1 or I_2.

Table 2 compares the correlation coefficient (multiple r), the adjusted correlation coefficient (adjusted r sq) and the overall F* (the criteria for this one also being "the higher the better') for three regression equations, all of which include L_1 and M_1 as X_1 and X_2 but differ by X_3, this being either I_1, or I_2 or M_2. Clearly all criteria suggest I_2 as third variable.

Metric Sets	Multiple r	Adjusted r sq	Overall F
L_1,M_1,I_1	0.9729	0.9238	41.4354
L_1,M_1,I_2	0.9814	0.9474	61.1418
L_1,M_1,I3	0.9586	0.8843	26.4805

Table 2. Criteria for selecting the 3rd variable

Table 3 shows also the partial determination coefficient (which accounts for proportionate reduction in the variation of Y after another X is added to the model) for X_3, X_3 being either I_1or I_2, when L_1 and M_1 are already included in the model: again I_2 emerges as the strongest candidate, because its introduction in the model provides the largest contribution in the reduction of the variation of Y.

Partial Determination Coefficient		
X_3	Jury Test #1	Jury Test #2
I_1	0.3584	0.1110
I_2	0.5576	0.6905

Table 3. Partial Determination Coefficient For The 3rd Variable

CONCLUSION

A method for analyzing and predicting the sound quality of seat adjusters has been developed and this technique could easily be applied in other situations and is especially suited to electric motor driven equipment.

Analysis of the noise produced by adjusters during vertical operation has shown it to be sufficiently different in character as to require a different coefficients for accurate evalutation.

Further work is being done in the area of relating sound metrics to vibration data on the mechanism to allow a more rapid analysis of a design in a production environment where sound measurements are impractical.

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