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# The Development of a Sound Quality-Based End-of-Line Inspection System for Powered Seat Adjusters

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## ABSTRACT

In recent years, the perceived quality of powered seat adjusters based on their sound during operation has become a primary concern for vehicle and seat manufacturers. Historical noise targets based on overall dB(A) at the occupant's ear have consistently proved inadequate as a measure of the sound quality of a seat adjuster. Significant effort has been devoted to develop alternative sound quality metrics that can truly discriminate between "good" and "bad" seat adjusters. These new metrics have been successfully applied for some years by product development engineers in test labs. However, in the assembly plant the sound quality of the seat adjuster is still assessed subjectively by an operator at the end of the assembly line. The main problem with this approach is not only the lack of consistency and repeatability across large samples of seat tracks, but also the fact that the only feedback provided from the end-of-line to the product development team is of subjective nature. This subjective information is of little help for the engineers who have to diagnose and remedy the problem. Additionally, since sound quality has become one of the main reasons for rejection at the end of the assembly line, there is the need for integrating sound quality performance checks with the standard quality control or functional checks in the manufacturing environment. Therefore, the new challenge for the seat adjuster manufacturer is to implement at the end of the assembly line an automated Sound Quality-based inspection system that relies exclusively on objective parameters. The authors of this paper have devoted a lot of effort toward developing such a system, and this paper will describe and discuss the main issues related to its design, implementation and validation.

## INTRODUCTION

The technology of automated end-of-line inspection systems is well established. Multiple inspection criteria have been implemented in recent years in PLC controlled stations to replace, as an example, subjective visual checks of quality and integrity of the product or to monitor the quality of the component by means of its surface vibration. Several inspection systems are commercially available which apply machine monitoring techniques such as vibration spectra, cepstrum, order tracks, etc. Only very few of these systems also rely on some measurement of noise and, even less often, of sound quality perception.

However, sound quality has become in the last 10 years or so a fairly important factor that is accounted for at all stages of the product design and development. In the engineering community, statements like "The customer doesn't like how it sounds" or "The competitive product sounds much better" are fairly common. These statements generally trigger wide scale troubleshooting activities specifically aimed at improving the acoustic image of the product, without of course compromising its other performance characteristics.

Sound Quality is nowadays one of many performance targets, and engineers in Research and Development Centers and their counterparts in the Design groups have become very familiar with most sound quality techniques. However, this expertise has been limited so far to product design and development activities, and no attempt has been made to apply it to the end of an assembly line in a plant environment.

The main challenges that a "traditional" end-of-line inspection system in a plant has to face are related to the constraints of cycle time, to the robustness and reliability of the hardware, to the detection algorithms and to the data management. When Sound Quality criteria are added to the picture, then other important factors have to be taken into account, such as maximum acceptable background noise in the test cell, correlation of subjective and objective sound quality criteria, computation time and management of large set of data (time histories).

The objective of the project described in this paper is to develop an automated inspection system that can reliably replace the sound quality judgment of an operator at the end of the line. The system "accepts" (Pass) or "rejects" (Fail) the seat adjuster under test based on some predefined sound quality acceptance criteria. The Pass/Fail judgment along with other meaningful data is then stored in a database where the seat adjuster is identified by its serial number.

In order to achieve this objective, the following steps have to be accomplished:

1. Define the system functional requirements
2. Identify all sub-systems and components (hardware and software) of the system
3. Identify roles and responsibilities of all parties involved in the project
4. Define a time schedule agreed upon by all parties.
5. Define specifications for the acoustically isolated test enclosure
6. Define data acquisition and post-processing techniques and relevant sound quality metrics to be used by the Pass/Fail criteria
7. Define Pass/Fail algorithm(s)
8. Configuration and implementation of required hardware and software
9. Integration of hardware and software components and test of whole unit in laboratory
10. Installation of whole unit(s) in plant and test with high numbers of adjusters

It is important to point out at this point that the process outlined above is independent from the type of product that is under test and could apply to the development of any sound quality-based end-of-line inspection system.

## SYSTEM FUNCTIONAL REQUIREMENTS

The functional requirements of the system clearly drive the choice of the hardware and software components. In the case of the powered seat adjusters, the functional requirements were defined by the seat manufacturer and included, as an example (but were not limited to):

OPERATION – 100% of adjusters, automated inspection, loaded with mass to simulate occupant, all motions operated independently, full travel tested.

DATA TO BE ACQUIRED – Speed of operation, current signature, noise and vibration

INSPECTION CRITERIA – Speed of operation, maximum current draw, sound quality and vibration.

MANUFACTURING FEEDBACK – All Passed adjusters are in shipping position, all Failed ones in non-shipping position. Handling fixtures for packaging have to be coordinated not to accept Failed adjusters. Pass/Fail label printed with main Pass/Fail criteria per each motion. Individual sound quality metrics and Pass/Fail criteria are stored in Company server, along with possible cause of Failure.

The functional requirements were defined by the seat manufacturer by considering three different objectives for the sound quality based inspection system:

1. The system replaces subjective Pass/Fail of operator
2. The system has to provide a feedback in terms of possible cause of failure. This information can then be used by R&D and Product Development engineers to focus the troubleshooting activities on the failed adjusters
3. A modified version of the inspection system can then be used by R&D engineers to develop sound quality targets for each component (gears, motors) and by the components' suppliers to test and validate their product.

It is clear that the impact of the inspection system goes beyond the boundaries of the end-of-line environment. While this may be the primary objective in the short term, the goal of the seat adjuster manufacturer in the medium and long term is to provide a higher quality product (better sound) at lower cost. Improved sound quality can be achieved only by establishing sound quality targets agreed upon by the OEM. The targets can then be propagated down to the individual components so that changes in performance can be caught before adjusters are fully assembled.

## THE COMPONENTS OF THE SYSTEM

A sound quality inspection system for powered adjusters is made of the following components:

- A test station that incorporates specimen load/unload, seat track hold down requirements, power to activate the seat adjuster, and a PLC to initiate motion and perform functional checks
- An acoustic enclosure within the test station to isolate test specimen from environmental noise
- Transducers and signal conditioning hardware
- End-of-Line Test System which initiates/supervises via a PLC the test sequence to include seat track motion, data acquisition, and other activities (calibration, test setup, man/machine interface, standard operation). This system includes bar code scanner to acquire serial number and pass/fail label printing capabilities
- A Sound Quality Test System, which interfaces to End-of-Line Test and includes a microphone calibration module, a high sampling frequency data acquisition module, a sound quality metric calculation module, a sound quality assessment module and a sound quality database module

- Sound Quality criteria for Pass/Fail

Each of these components requires a specific expertise, therefore multiple parties are involved in the design and development process. As an example, for the project described in these pages, the main responsibilities were assigned as follows:

- All mechanisms and hardware necessary to handle and move the seat adjuster from the end of the line to the test cell and then out of the test cell are supplied by the seat manufacturer
- The test station along with the End-of-Line Test System is supplied by the inspection station manufacturer
- The noise and speed data acquisition, the sound quality metrics, the pass-fail logic, and the database modules are provided by the NVH partner.

## REVIEW OF SEAT ADJUSTER SOUND QUALITY

It is outside the scope of this paper to discuss in detail the different factors which affect the sound quality perception of DC-motor powered mechanisms in general and seat adjusters in particular. This field has been investigated for years now and there is a widespread agreement in the NVH community on the factors which influence seat adjuster sound quality. Several papers have also been published on the subject (a few examples are given as references 1, 2 and 3) and, in general, we can summarize their conclusions for the "non-NVH engineer" as follows:

1. The A-weighted Sound Pressure Level does not allow to discriminate between good and bad seat track sound quality
2. DC-motor RPM is an important factor which affects the perceived sound quality of the seat track.

Let's try now to understand why.

First, all considerations that follow apply to the travel portion of the seat adjuster motion and exclude the transients at start and stop. Figure 1 displays a typical time history of the sound pressure measured during the motion of a seat adjuster sub-system. The so-called travel portion is the range of the time which lies between start and end transients. It is important to differentiate between travel portion and transients because they induce different perception problems from a sound quality and tactile standpoint.

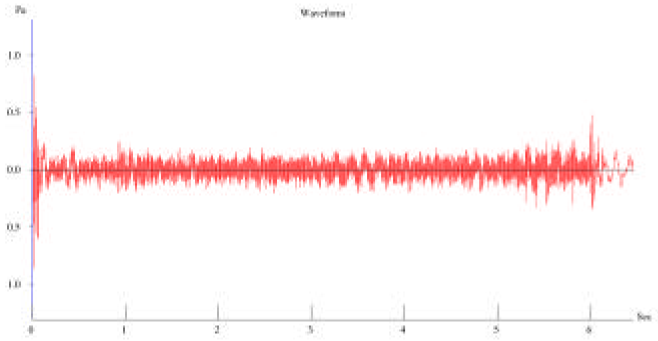

Figure 1. Time history of sound pressure measured during motion of a seat track

During the travel of any sub-system, the following features are perceived as annoying:

LOUDNESS - In general, this is still the most important factor. Loudness is measured by the psycho-acoustic metric Transient Loudness in sones (ref. 4), and quantifies the perception of loudness much better than the A-weighted Sound Pressure level. Existing end-of-line seat adjuster inspection systems rely, from the noise standpoint, exclusively on average Sound Pressure Level in dB(A). Figure 2 shows an example of loudness functions for a few seat tracks.

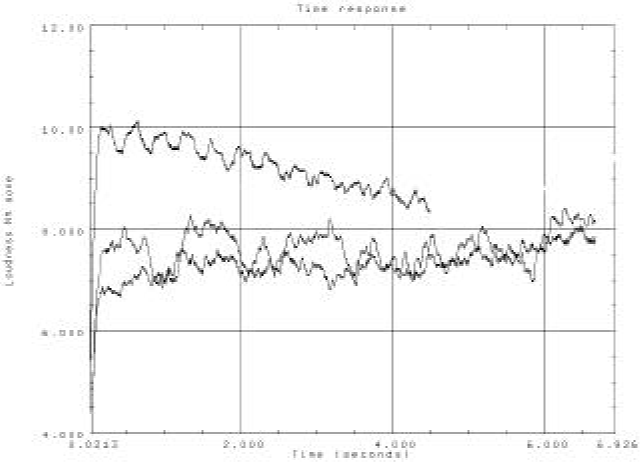

Figure 2. Loudness functions (sones) of different seat track motions

However, when the seat adjuster is quiet, frequently other features become noticeable, such as:

MODULATION – It includes both Amplitude and Frequency Modulation. Modulation relates to those sound quality terms widely used in the seat adjuster manufacturing community such as “wow-wow”, “scraping”, “thumping”, “sewing machine”. This is probably the most common feature in seat adjusters and can have different origins. As an example, while it is known that amplitude and frequency-modulated sounds may sound very similar, in reality the underlying mechanisms may be not only different, but possibly even independent from each other. Modulation, both AM and FM, is generally related to the gear reduction mechanisms in the track and the modulation frequencies generally coincide with the gear-mesh frequencies of the gear reduction systems.

The psychoacoustic metric Fluctuation Strength quantifies primarily the amplitude modulation in the signal, so it was not found to be a good descriptor of FM modulation. An alternative metric, called Fluctuation Strength FM (or FSFM), was therefore developed in past project work by some of the authors which is specific for DC-motor powered mechanisms. This new metric is based on a combination of modulation of the RPM signal and of the tonality in the acoustic signal. Figure 3 shows, as an example, the RPM functions of two sub-systems, one with a strong 5-Hz modulation (FSFM=3.3) and the other with a much less pronounced modulation (FSFM=0.55).

On the other hand, an example of strongly AM seat adjuster sound is displayed in Figure 4. The modulation perception of this sound is not dissimilar from that induced by the sound of Figure 3. However, the underlying mechanisms are different.

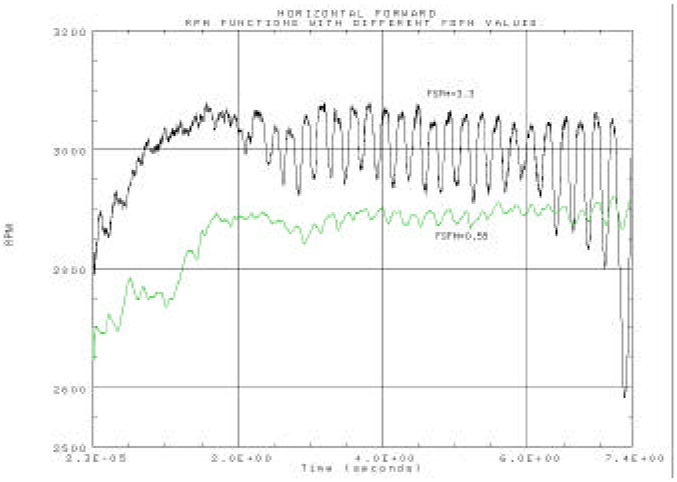

Figure 3. Example of DC-motor RPM functions with strong 5-Hz modulation (FSFM=3.3) and with little modulation (FSFM=0.55)

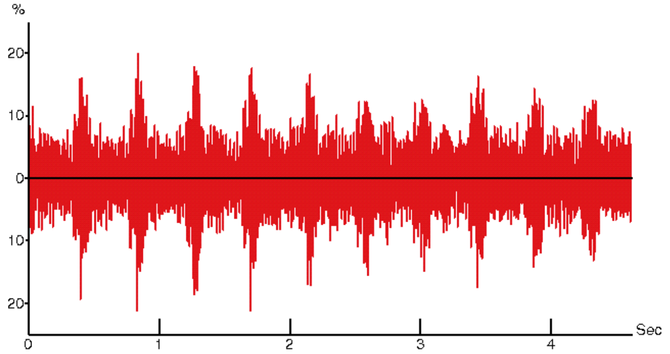

Figure 4. Example of seat adjuster noise with 3-Hz amplitude modulation

SPEED VARIATION - It quantifies the overall change of speed of the DC-motor throughout the travel. This is another metric derived in previous project work by some of the authors (1). Ideally, the speed of the motor should be constant. However, due mainly to geometric misalignment and adverse mounting conditions, the load applied on the motor can change greatly during the travel. This load fluctuation causes a speed variation to occur. Significant changes of speed induce perception of “weakness” of the motor (‘will it make it?”), of inconsistency, etc., and affects the “image” of the seat track. The metric Speed Variation is a combination of speed change depth, rate (in RPM/s) and position (when it occurs during the travel), all parameters being related to the RPM function of the DC motor. Even though the metric Speed Variation is not computed from the acoustic signal, it was found to be correlated to the preference expressed by a jury of more than 80 people. Figure 5 shows an example of high and low values of SV. The displayed functions are in units of RPM change relative to the RPM at beginning of travel.

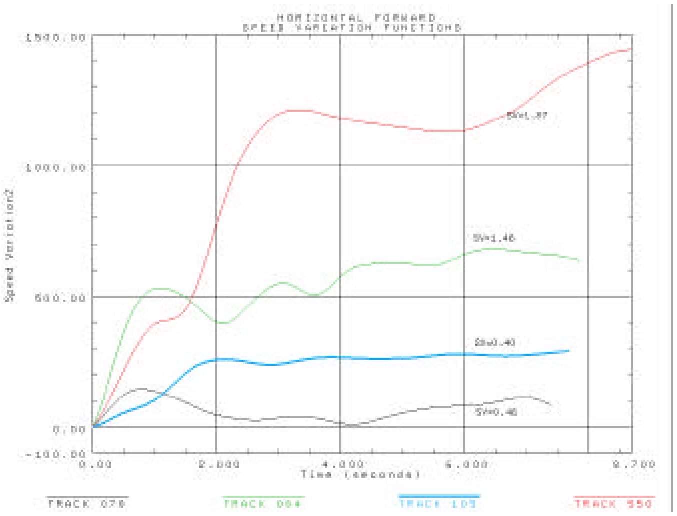

Figure 5. Example of DC-motor RPM functions with different degrees of Speed Variation

WHINING – This characteristic is in general related to the occurrence of a resonance of either the DC-motor or other components (motor bracket, etc.) and one or more tonal components (motor orders) become dominant. It can be measured by metrics such as Tonality and Spectrum Balance. Figure 6 shows the FFT spectrogram of a sub-system with whining. Note the high level of the 20th order.

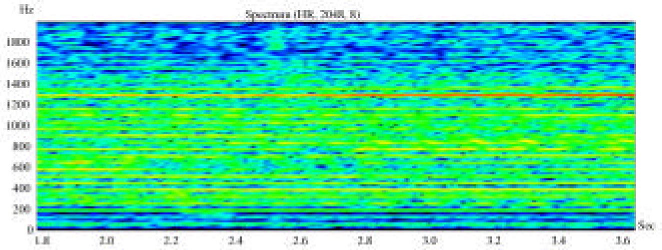

Figure 6. FFT-spectrogram of seat adjuster noise with whining. Note high 20th motor order.

RATTLE – It is generally caused by imperfections of the gears and it is measured by statistical parameters of the distribution of the time history of the sound pressure, such as kurtosis. Figure 7 shows the kurtosis function of a seat adjuster sub-system with a lot of rattle and one with much less rattle.

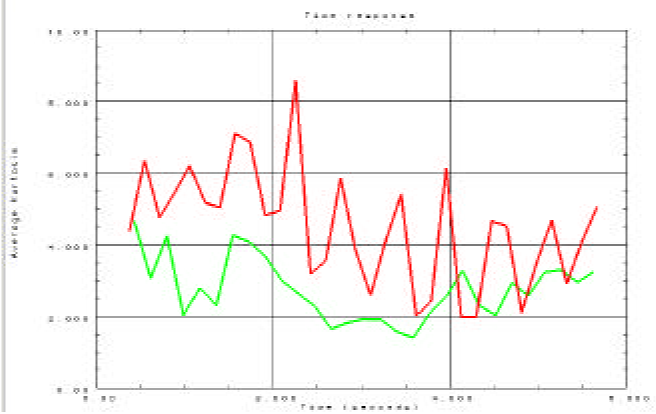

Figure 7. Kurtosis functions of seat adjuster with strong rattle and with mush less rattle.

One final but important observation: from all functions displayed above, it can be seen that the acoustic signature of a seat track sub-system is not guaranteed to be stationary. This has rather important consequences on the design of the inspection system as well as on the signal processing techniques employed:

1) the system has to be capable of testing the motion of each sub-system in its entirety

2) average metrics values may be inadequate to describe the dynamic behavior of the seat adjuster.

## THE TEST ENCLOSURE

One of the most important steps in the development of a reliable end-of-line sound quality inspection system is the design of the enclosure in which sound quality and functional tests will be conducted. This is due to two main factors:

- Correlation between laboratory and plant environment
- Overall project timing schedule

CORRELATION BETWEEN LABORATORY AND PLANT ENVIRONMENT - All sound quality investigation work is usually carried out in the NVH lab in a highly controlled and idealized environment. In order to apply to the end-of-line environment the sound quality knowledge derived from these studies, it is necessary to do some correlation work. The main differences between the NVH lab and the end-of-line environment are:

Transducers - While in the Sound Quality lab, all noise recordings are made using an artificial binaural head, in the test cell on the plant floor due to space limitations, material handling issues, costs etc., only microphones can be used and it is potentially limited to just one microphone. Furthermore, in the test cell, the actual distance allowable between the microphone and the main noise sources (the DC motors and gearboxes) is much smaller than the 25-30" standard employed in the Sound Quality lab.

In order to verify the feasibility of using a single microphone in the inspection system, measurements of several current production seat adjusters were carried out with a single microphone in a seat assembly plant. Along with these measurements, the Pass/Fail judgment of the operator was also recorded for each tested track. These data were then used to verify whether metrics computed from a single microphone would still be representative of the sound quality perception. The computed metrics were entered into a preliminary Pass/Fail algorithm, and the results compared to the Pass/Fail judgment of the operator at the end of the line. Additionally, for these measurements, the microphone was located at a position close to the motors (noise source). Subsequently, this activity was useful to verify the effect of microphone location position on the sound. The goal was to find the closest position for the microphone that was still representative of what an operator sitting on the seat or standing in front of it would perceive.

Background Noise - The background noise in the test cell at the end of the assembly line will most likely be higher than the background noise in the Sound Quality lab. Even if the test cell offered high Transmission Loss values, with time this performance will degrade due to wearing of the seals etc. For this reason, it is not realistic to expect low background noise, therefore the system has to be “de-sensitized” as much as possible from extraneous (to the seat adjuster) noises. At the same time, the test cell should be designed in order to ensure in any event low background noise levels.

Therefore, the first step was to define the acoustical specifications for the test enclosure. These specifications depend on the surrounding environment, that is higher Transmission Loss will be required if the enclosure is in a noisy area (i.e. stamping plant), while less stringent specifications would be enough in case the ambient noise is lower (i.e. assembly plant). For the development of the system described in this paper, a stamping plant and an assembly plant where the assembly lines of the new seat adjusters could possibly be installed, were visited in order to measure the background noise in selected areas. At each measurement location in both plants, the noise was recorded for a few minutes at different intervals and at different times during the day in order to capture the possible variation of the noise level during a typical workday. Each noise recording was than analyzed in terms of peak-hold 1/3 octave spectrum. An example of the peak-hold 1/3 octave spectrum of the ambient noise in one of the plants is given in Figure 8.

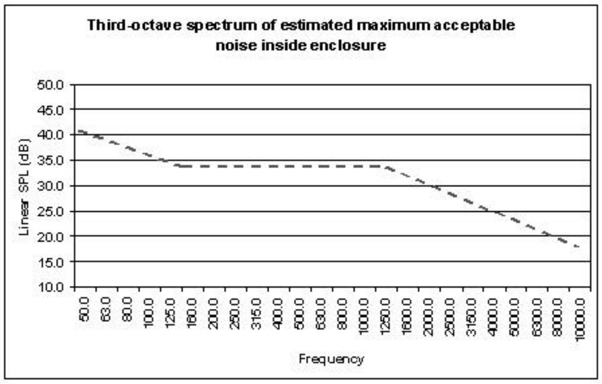

Figure 8. Example of noise Peak-hold 1.3 octave spectrum of ambient noise outside the test enclosure

Next, the noise from several seat adjusters was averaged to derive a typical, average seat adjuster noise spectrum in 1/3 octave that could represent the item to be tested in the enclosure. The seat adjuster spectrum utilized was the average of a wide variety of seat adjusters and seat adjuster designs, from the very quiet to the louder ones. The amplitude of the average spectrum was then modified to reflect different distances of the microphone from the source, under the conservative assumption that the sound field in the enclosure is free (6 dB attenuation per doubling of distance). The maximum allowable background noise in the enclosure was then derived by following the rule of thumb that the background noise needs to be at least 10 dB below the noise that one wants to measure.

On the basis of the peak-hold spectrum present outside the box and of the maximum allowable background noise inside the enclosure, a series of curves of required Insertion Loss (function of different external ambient noises) were derived. One of these curves is shown in Figure 9 (dashed) where the Transmission Loss of a lightweight double-wall is also shown for comparison purposes (dotted) (ref. 5).

From these curves it seems clear that while the required IL at medium-high frequencies can be achieved by, as an example, double-wall type of solutions, this solution would not guarantee the required acoustical isolation at frequencies lower than 500 Hz. In order to achieve higher level of isolation at lower frequencies, the mass of the barrier has to be increased or an additional massive barrier needs to be added around the enclosure. In other words, and this is especially true if the inspection systems are installed in a noisy area, it is suggested to isolate the end-of-line sound quality inspection stations by putting them in a separate room.

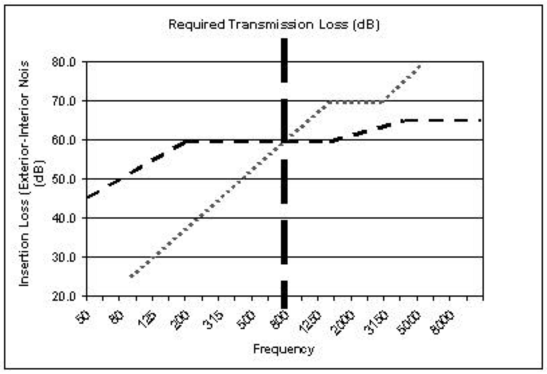

Figure 9. Required TL and TL of light weight double-wall.

OVERALL PROJECT TIMING SCHEDULE – Once the supplier of the acoustical test cell is selected, in general the delivery time for one or multiple units is on the order of magnitude of several weeks, possibly even of few months. It is therefore very important that the test enclosure is defined and its supplier selected in the early stages of the project.

## THE DATA ACQUISITION SYSTEM

The data that need to be acquired are:

- Noise
- DC-motor current
- Acceleration
- Position (of adjuster during travel) and speed of travel

The data acquisition system is made of two modules: one to acquire the basic adjuster position and current data (low sampling frequency), the other to acquire the time history of microphone, accelerometer and AC and DC-coupled current (high sampling frequency). The high sampling frequency is required in the second module since the sound quality metrics are computed over the whole audible frequency range.

The sound quality module used by this system makes use of a 4 channel DSP module with a sampling frequency of 44.1 kHz. and real time acquisition of 20 seconds per channel. This is another important requirement for the system since the sound quality features of the seat track may change considerably during the travel (due to their non-stationary nature), therefore the sound quality has to be monitored for the entire duration of motion.

The motor RPM is derived from the AC-coupled current to the motor. From the acquired time histories sound quality and RPM functions are computed by external off-the-shelf software routines.

## THE PASS/FAIL LOGIC

Two types of Pass/Fail logic can be used:

1. Overall Preference rating. In this case, the preference rating for each tested seat adjuster is estimated by combining the dominant sound quality metrics in a multiple linear regression equation. The equation will look like

   $$\Pr ef_{SQ} = a + b_1 X_1 + b_2 X_2 + .... + b_n X_n$$

   where $X_1, X_2, \ldots X_n$ are the linearly independent sound quality metrics, and $\alpha, \beta_1, \beta_2, \ldots, \beta_n$ are the regression coefficients. The estimated preference is a number (rating) referred to a linear scale (i.e. 0-10, -3+3, 1-7 etc.).

   The clear advantage of this approach is that it is easy to understand and the preference rating can be used as a "SQ label". However, since any given preference rating can result from different numerical combinations of the metrics in the equation, it doesn't provide specific information on which feature(s) cause the adjuster to fail.

   In the last 10 years, a multitude of papers have been published in which regression equations modeling the sound quality preference of vehicles, components and other automotive and non-automotive products were derived. These regression equations are very popular in the engineering community, because they allow us to translate subjective judgments into objective, single numbers. However, they should not be misused, these are statistical relations, not mathematical ones, therefore they are appropriate for understanding and modeling trends of behavior, but are much less adequate to establish rigid numerical thresholds.

2. Absolute threshold value for each metric. In this case, a threshold value is defined for each metric that quantifies an objectionable sound quality feature. These threshold values can be defined based on scales of sound quality preference that are either absolute (apply to any seat adjuster) or relative to the seat adjuster type and vehicle class. This is a more rigorous set of criteria than the regression equation and it provides clear indication of which features make the adjuster pass or fail.

In order to derive any of the above logic, and to validate the logic against a sizeable population of seat tracks, it is necessary to compute a significant amount of indices and descriptors and to extract meaningful information from this database. This activity is very time consuming and prone to error if done manually. In order to increase the efficiency and reduce the risk of error, several new routines were developed by some of the authors to manage the metrics data, to extract from them and store all relevant information, and to organize these results in user-friendly environment (i.e. Excel) where different algorithms may be tried. This activity is fully described in a companion paper (ref. 6).

At the time of writing, the Pass/Fail algorithms based on sound quality metrics have been successfully tried on two types of seat track adjusters in the NVH laboratory.

A final validation in the plant with a high number of seat track adjusters (> 2000) is expected by January 2001.

A first prototype of the SQ-based inspection system is shown in Figure 10.

Figure 10. First prototype of SQ-based EOL inspection system.

## CONCLUSION

The feasibility and methodology of an automated end-of-line Sound Quality-based system has been demonstrated. Further, it has been shown that such a system, when integrated with Quality Control measures and software, can be used to track and contain potentially rejected seat adjusters, as well as help ascertain where the fault may lie. Further, utilization of such a system allows the seat adjusters' mechanical and SQ performance to be monitored, tracked, and documented.

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