Squeak and Rattle – State of the Art and Beyond

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Modern trends in noise control engineering have subjected the automobile to the "drained swamp" syndrome. Squeaks and rattles (S&R) have surfaced as major concerns. Customers increasingly perceive S&R as direct indicators of vehicle build quality and durability. The high profile nature of S&R has led manufacturers to formulate numerous specifications for assemblies and components. Even so, a large majority of buzz, squeak and rattle (BSR) issues are identified very late in the production cycle, some often after the vehicle is launched. Traditionally, the find-and-fix approach is widely adopted, leading to extensive BSR warranty bills. The design-right-the-first-time approach must replace the find-and-fix approach. Due to the vast breadth and depth of S&R issues, a comprehensive summary of the present state of the art is essential. This article includes a literature survey of the current state of the art of S&R and discusses the methods available to further advance it. Dedicated and focused attempts to advance the state of the art require the formulation of an integrated design strategy that attacks S&R during the earliest stages of design and development, leading to substantial savings in fix and warranty bills.

The sound inside a passenger cabin is composed of many elements, a fundamental element of which is irritating noises comprised of buzzes, squeaks and rattles. Customer perception of buzz, squeak and rattle (BSR) is measured by Things Gone Wrong (TGW), warranty claims and JD Power surveys.[1] A market survey as early as 1983 reported squeaks and rattles as the third most important customer concern in cars after 3 months of ownership.[2] The absence of S&R provides direct positive feedback to the customer of the perceived vehicle build quality. In the highly competitive automotive market, a superior S&R strategy can easily poise manufacturers for market leadership through customer perceived initial build quality and published JD Power survey rankings. The battle against S&R is not an easy one. Modern advances regularly reduce the general level of other major sound sources such as the powertrain, wind, road and tire, both actively at the source and passively at the receiver end. The trend towards lightweight body construction and lightweight materials combined with the increase in general content in the subsystems keeps growing. Controlling S&R is thus an even bigger challenge. Vehicle owners of the new millennium will demand a tremendous increase in the instrument panel (IP), seat and door subsystem content. Electric cars of the future will highlight even the most subtle of S&R issues because of the general low level of powertrain noise and the use of lightweight components inherent to their design.

Currently, manufacturer warranty bills from S&R issues are estimated to be about 10% of total things-gone-wrong costs.[1] Instrument panels (IP), seats and doors are responsible for over 50% of the total S&R problems, with IP being the main offender.[3] The traditionally applied "find-and-fix" approach methodology used to obtain quality improvements has resulted in a tremendous increase in product costs with little proven durability. The 'band-aid' corrective actions often depend on operator installation accuracy. The best resolution, generally onetime tooling revisions, occurs late in the production cycle and is prohibitively expensive. Because of the high profile nature of S&R, manufacturers have formulated numerous specifications for S&R performance of assemblies and subcomponents. These efforts have naturally focussed on long term durability, considering the effects of multiple and simultaneous environments. Over the years, manufacturers have borne the high cost of maintaining large shakers, four post simulators, drive-in environment chambers and semi-anechoic chambers. These high cost 'legacy' systems have helped to reduce S&R, but only in the form of find-and-fix solutions that are slow and costly. Hence, the need exists for a design approach that targets S&R. Significant gains can be achieved by approaching S&R from a design perspective upstream in the design and development cycle. A comprehensive survey reveals a scarcity of published literature aimed towards attaining such a goal. Due to the relatively recent importance that S&R has garnered, it is hardly surprising that all the applicable published literature spans only the past decade. It is important to be aware that the proprietary nature of a company's S&R know-how only adds to this void. Nevertheless, the vast breadth and depth of S&R issues require the formulation of an extensive design-intensive strategy to combat BSR and hence advance the state of the art.

Squeak & Rattle – Background and Theory

Squeak is a friction-induced noise caused by relative motion resulting from a slipstick phenomenon between interfacing surfaces. The elastic deformation of the contact surfaces stores energy that is released when the static friction exceeds the kinetic friction, producing the audible squeak noise. The slipstick cycle usually occurs at lower frequencies induced by suspension inputs but the release of energy produces a vibration of the surfaces that causes audible squeaks in the 200-10,000 Hz range. Generally, there are two squeaks per cycle. For a suspension-hop-induced squeak, the frequency of the sound bursts would be twice that of the hop frequency. The amplitude and frequency of the squeak depend on a host of complex factors such as material constituents, coefficient of fiction, normal load and load history, sliding velocity, inertia and thermal effects, wear characteristics, temperature and humidity conditions, etc.

Rattle is an impact-induced phenomenon that occurs when there is a relative motion between components with a short loss of contact. It is generally caused by loose or overly flexible elements under forced excitation. Impacts are caused when surfaces close to each other move perpendicular to each other due to insufficient attachments or insufficient structural strength forcing repeated separation and reestablishment of contact. As with squeaks, the exciting force is predominantly road surface induced, which forces components to vibrate inertially. This motion results in impacts if the tolerances are inadequate, vibration is excessive and/or the subassemblies are very close. Of course, the impacts will only be perceived as noise if surface areas of components adjacent to the impacts are large enough to radiate audible sound-power levels. The frequency range of audible rattles is between 200-2000 Hz. Higher frequency rattles are often perceived as *buzz*. Generally, there is one rattle per cycle. For a suspension-hop-induced rattle, the frequency of the individual sound bursts would be the same as the hop frequency.

Causes of Squeak & Rattle

Almost all S&R can be attributed to structural deficiencies, incompatible material pairs or poor geometric control. The

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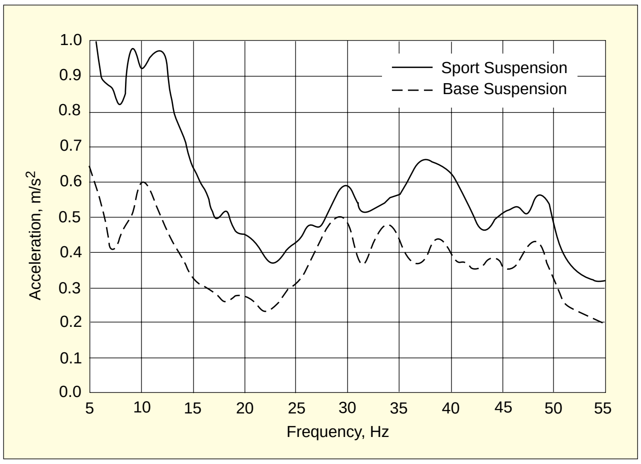

Figure 1. Effect of suspension stiffness on IP response.

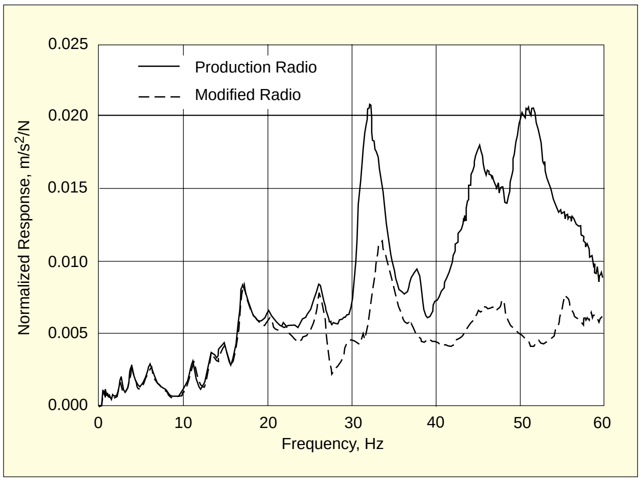

Figure 2. CD player/radio vibration reduction.

underlying aspect of S&R is that they are caused due to relative motion exceeding a threshold value. Relative motions do not always cause S&R, but S&R are always caused by relative motion.

Relative motions due to structural deficiencies result from insufficient stiffness, excessive input forces or poor modal alignment. A stiff suspension causes input forces to be large. In a study conducted by the authors, a vehicle with a sport suspension and low profile tires was found to produce approximately 30% higher response levels on the IP than the same vehicle with its base suspension and normal tires. The average substrate-response levels for the two vehicle suspension configurations are overlaid in Figure 1.

Insufficient global, local and attachment stiffness can contribute heavily to S&R issues. The authors were involved in an IP mounted compact disc (CD) player skip issue. The root cause was determined to be insufficient IP global bending stiffness (largely fore/aft) and poor CD/radio player attachment stiffness. On a damaging rough road section at the proving grounds, 16 skips were recorded. After incorporating a production feasible brace and reinforcing a local attachment, the number of skips was reduced by over 90%. The before and after modal analysis revealed the local radio and attachment amplitudes to have decreased by 60% over the affected frequency range, as shown in Figure 2.

The importance of static stiffness both global and local cannot be neglected. Major suspension input frequencies are below the resonant frequency of the components. An excitation at this frequency is countered only by the static stiffness value. It is therefore an important contributor that is often overlooked in the design cycle. If, during the design, a resonant frequency is targeted, it is possible that the static stiffness is insufficient. When a component with the same 'apparent' resonant frequency but with a lower modal stiffness is excited at frequencies lower than its resonant frequency, it will result in higher response levels. This is discussed in detail later.

Often the stiffness may be adequate but poor modal alignment with other major body/engine/seat modes causes high response levels that produce damaging relative motions. Nolan and Sammut[2] have shown this, using an example of a door system.

By utilizing good design principles, relative motions can be minimized but not eliminated. Often, the functionality of the subsystem or component requires adjustments – for example, seats need to slide and retract, door latches and window regulators need movements to satisfy their functionality. Wear of such systems produces looseness over the life of the vehicle. Temperature and humidity conditions cause dimensional variations in components especially those containing elastomers. Due to such conditions, material pairs are bound to interact. Depending on their compatibility (chemical compositions, surface properties, environmental conditions, etc.) the rubbing of the interfaces can produce audible squeak noise while impacts can produce rattles.

S&R can also occur from a host of factors related to the geometry. The inappropriate separation of the two surfaces is likely to lead to S&R and is manifested by poor tolerances at the design and/or the production level. Often, manufacturing tolerances do not maintain the design intent during the assembly process due to poor quality control. Another geometric factor that could possibly lead to S&R is the shape of components – usually IP or door trim. Components with large untreated surfaces can provide very favorable sound-radiation surfaces that amplify the otherwise subtle S&R.

Prevention of Squeak & Rattle

Studying the causes of S&R, it is obvious that effective S&R prevention efforts can be directed at four broad categories comprising structural integrity, material pair compatibility, manufacturing control and 'smart' design.

Structural Integrity. As relative motions cause S&R, minimizing them effectively controls S&R. By using smarter structural design, S&R can be heavily reduced. Reduced S&R warranty bills can easily offset the initial cost of method development and implementation. Superior structural integrity implies adequate static and dynamic stiffness, both global and local. Stiffer is generally better but too stiff is also too expensive and too heavy.

Superior dynamic stiffness needs to go hand in glove with adequate modal alignment and mode shape continuity. Over the last several years, the focus on vibration management has been directed toward modal-alignment strategies.[1] Using the resonant frequency of a vehicle structure or component as a parameter to measure NVH quality of a vehicle has proven to be valuable in many structural NVH issues including S&R. The focus has been to isolate modal frequencies and minimize interaction and excitation. Nolan, et al., Reference 1, provide a typical modal alignment chart.

Benchmarking is the cornerstone activity of establishing static and dynamic stiffness targets. The target setting procedure follows the benchmarking process. This approach was first introduced by Nolan, et al.[1] They have alluded to the fallacy of the solely frequency based target setting approach in some detail and introduced the response based approach. Incomplete comparisons result if the resonant frequency and mode shape are derived from a modal analysis because of differences in 'classical' behavior. Say, for example, that the target vehicle has a continuous, global and symmetric torsion at 22 Hz. The analyst also picks a 22 Hz torsion mode for the subject (test) vehicle under development but this mode is not as global, continuous and symmetric due to higher front-end torsion. The modal mass participating in the torsion mode is therefore much higher for the target vehicle than the subject vehicle. Because both modes occur at the same frequency, it follows that the effective modal stiffness of the target vehicle

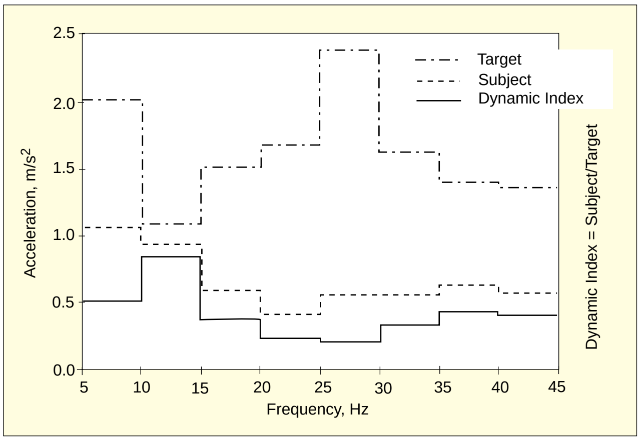

Figure 3. Target & subject functions and dynamic index.

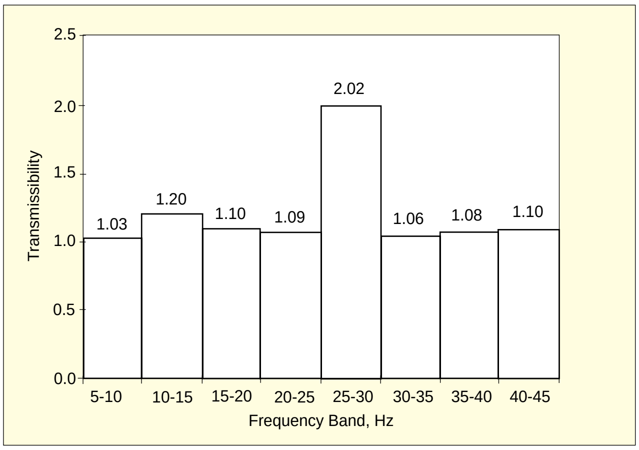

Figure 4. The effective amplitude transmissibility function.

is larger than that of the subject vehicle although the frequency based approach predicts torsion at the same frequency. This suggests that the modal mass, modal stiffness, modal damping, static stiffness and other derived parameters must be incorporated into the target setting process in addition to the resonant frequency.

Kavarana, et al.,[4] have presented a comprehensive response based target setting approach applied to IP S&R prevention. This was accomplished using a best-in-class target vehicle and a subject (test) vehicle. Data were acquired over a variety of road surfaces and in the laboratory on a body-in-gray (BIG) with the IP and on the lone IP itself. Static stiffness tests were performed on the body and the IP. A systems approach was employed for target setting and cascading. Several useful dynamic functions were proposed as shown in Figures 3 and 4. The effective transmissibility of the IP and IP components was quantified at each cascade level for the two vehicles. The deficient structural link in the IP design was identified. Using a systems approach, targets were cascaded from the full vehicle to the component level. An effective IP development strategy was identified. Requisite structure to the IP was provided by the cross-car-beam (CCB) that included fore-aft and vertical supports. Major component masses that were attached to the CCB performed better than components attached to the IP substrate. The IP substrate should not perform as a load-bearing member but as an aesthetic cover. These and other important design guidelines were provided. For seat subsystems, Frusti, et al.,[5] have published S&R requirements.

The process of target cascading and/or target synthesizing follows the target setting process. This is the most critical phase of the S&R prevention strategy. When successfully implemented, it can lead to tremendous savings in time-to-market and warranty costs. Cascading implies moving from the full vehicle system to the component level targets, while synthesizing involves moving from the component to the vehicle level

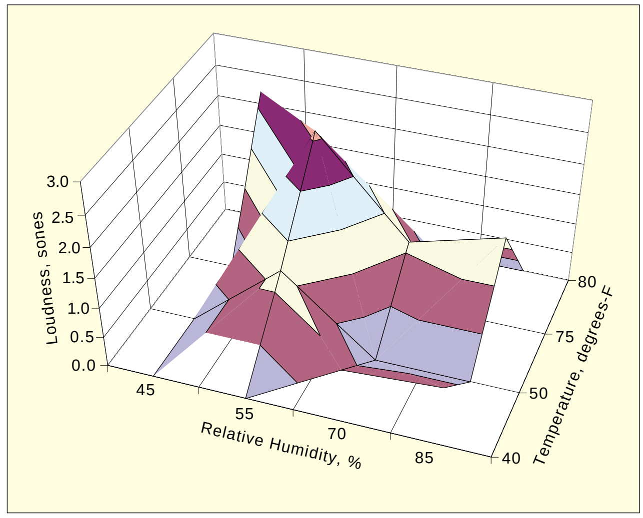

Figure 5. Squeak susceptibility of CP material.

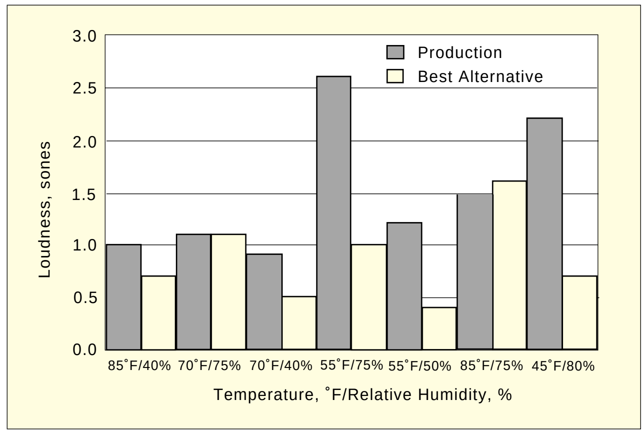

Figure 6. Squeak performance – CP vs. best alternative.

targets. To ensure the success of the target cascading/synthesizing process and reap the total benefits, it is essential that the process of target cascading and synthesizing is made integral with the computer aided engineering (CAE) design process. Without CAE support, target cascading and synthesizing can become a costly exercise that may be frowned upon by senior management. Often iterative initially, if strongly complemented with CAE, this activity has the potential to be the trump card for attaining superiority in S&R prevention.

Superior Material Friction Pairs. Since some relative motion is always anticipated, the judicious selection of material mating pairs will reduce the occurrence of S&R. Squeaks, itches or creeks, are generally caused at elastomeric contact locations such as windshield and backlight headers, roof/door weatherstrips, IP seals, etc. A fair amount of effort has been expended to find squeak-free elastomeric materials.[6] Because of the tremendous number of entities involved in the generation of the squeak, no single material is the ultimate *fix-all* solution. Manufacturers have tried several 'slip-coatings' and surface finish textures on elastomeric materials but only with limited success resulting from problems with wear and atmospheric durability. Research in this field has gravitated towards finding effective material friction pairs that minimize squeaks. Judek, et al.,[7] have published an extensive survey of the state of the art in this field. They have determined the mechanism and sensitivity of vehicle components and systems to squeak. They also describe computational experiments with material pairs and how they correlate to friction data from experiments. Eiss, et al.,[8] further utilized a friction test apparatus to develop a polymeric material pairing database for use in automotive systems. They aim to integrate the database into the automotive component design process (CAD/CAM/CAE) so that potential concerns can be addressed prior to critical design milestone freeze dates.

The authors have developed a similar apparatus that measures the squeak between sliding surfaces such as elastomer-to-glass and elastomer-to-metal (body panels) interfaces with the aim of finding superior material mating pairs. This system incorporates the simulation of different temperature and humidity conditions and different interference levels and angles in the presence of controlled sine or random excitation. The authors have performed a best-in-class study for seven different elastomer coatings on a convertible top weather strip. Using a variety of environments, the 'best' material was identified. The squeak was evaluated using Zwicker loudness in sones. Brines and May[9] have concluded that non-stationary Zwicker loudness is a good tool for objective quantification of S&R noise. Figure 5 shows the squeak susceptibility of the current production (CP) material to different temperature and humidity conditions. Figure 6 shows the performance of the CP material against the best alternative material. Two of the seven materials tested were found to be superior to the current production. The best alternative was found to perform very well in field trials but failed OEM coating durability tests. Therefore, the second best alternative had to be adopted. At this stage, such tests are the best option for evaluating material combinations. Juneja, et al.,[10] studied the effect of interference level and angles, temperature, humidity, input frequency and creep, using the same apparatus. Yang and Rediers have studied squeak behavior on fixed glass systems[11] on a similar apparatus.

Manufacturing Process Control. A good number of S&R issues occur due to poor manufacturing control or large process variability. Tighter control in manufacturing undoubtedly reduces S&R but usually at a higher cost. This is evident in the low S&R levels with luxury vehicles. Nolan, et al.,[1] have shown the wide dispersion in relative performance between different models marketed by manufacturers. Dispersion in quality is larger for an economy vehicle. Corporate best-in-class vehicles performed 30% better than average. Providing adequate tolerances and knowledge of effective manufacturing assembly feasibility at the design level can be very beneficial for S&R prevention. A *S&R Lessons-Learned* database from prior models can be immensely useful for this activity.

'Smart' Design. A smart design consists of several incremental factors that can provide effective solutions to niggling S&R issues. A number of smart design practices are employed as a result of poor experiences in past models. Often, design engineers compromise S&R over aesthetics when indeed a mutually acceptable solution is possible. A database of *S&R Lessons Learned* as well as one of effective *Competitor S&R Solutions* can prove invaluable to design engineers. Attention to small details pays high dividends in the S&R arena.

Certain shapes, especially those used in door system and IP trim, afford effective acoustic amplification resulting from multiple reflections. Other materials provide 'hard' acoustic reflection surfaces. Often, minimal sound damping surface treatments are effective at minimizing acoustic radiation and amplification. Sound barrier materials, placed cleverly between the source and receiver are beginning to be employed at several levels.

Other basic solutions must be borne in mind. Major structural members must be adequately supported. Component masses should be attached to major structural members. This was previously discussed with respect to an IP. Fasteners should be evenly and cleverly distributed. For example, a fastener for the IP substrate is more effective near a component rather than away from it. Adequate numbers of fasteners must be provided where required. Felt tape is known to be highly effective at S&R hot spots. Although the structural integrity of the component/subsystem may be adequate, felt tapes at historic hot spots effectively guard against environmentally related dimensional variations. Clips used to fasten trim on the IP are historic S&R hot spots. Innovative solutions to reduce the number of clips should be sought through a *S&R Lessons Learned* database, and a *Competitor S&R Solutions* database.

Integrated Squeak & Rattle Design Strategy

Figure 7 shows an overview of a proposed S&R prevention strategy that encompasses several facets and phases of vehicle development from concept to production. The formulation of an integrated design strategy of the future must aim to attain market leadership in S&R prevention. It will undoubtedly be based on a hybrid platform shared by CAE and testing. It will also heavily depend upon on-going research and development efforts to advance the state of the art. Critical feedback assessment from all phases of this strategy must be efficiently conveyed back for corrective actions which will ensure the success of this process.

Concept and Planning. At the concept stage, the pre-design occurs. Here, design innovations resulting from R&D efforts can be incorporated. The *S&R Lessons Learned* database and the *Competitor S&R Solutions* database are best utilized at this stage. Warranty records from previous models could serve an immense purpose while selecting systems and subsystems. Close attention should be paid to manufacturing feasibility and process control while accomplishing the design synthesis. The targets utilized in the prior model/program must be reassessed keeping in mind the changing technology, competitor positioning, market segment, customer needs, mandatory regulations and the like.

Design and Development. This is the heart of the whole process. CAE plays a cavalier role at this stage. The models for the systems and subsystems are individually simulated and the full vehicle is then synthesized. For the components and subsystems, the responses are calculated and the targets deployed. The dynamics of the subsystems and their continuity are verified. Targets are synthesized from component level or subsystem and subsequently to the full vehicle. It is not too far-fetched to assume that in the future this phase will evolve into a virtual proving ground, where all tests can be simulated on the computer in the presence of multiple and simultaneous environments.

Parallel with the CAE design and development, available and representative hardware can undergo testing. The mule vehicle can be assembled for full vehicle road testing. Material pairs selected in the design and development phase can undergo tests for S&R prediction. Using the results obtained from these initial tests, CAE models can be verified and updated.

Verification. This is the testing stage. Most representative hardware is now available. With the components and subsystems, the dynamic characterization is accomplished. Mode shape continuity as well as the frequency and response-based targets are now experimentally verified. Objective quantification is obtained and compared with subjective evaluations for S&R performance. Testing is accomplished at all levels: laboratory (shaker and 4 poster), on-road, durability courses, etc. Hurd[12] has proposed combining S&R evaluation with accelerated laboratory durability tests. S&R metrics that have been developed at the R&D level may be verified against subjective opinions. After the required tuning to the components, subsystems and the full vehicle, they are finally released for production.

Production. This is the critical "putting it all together" or the manufacturing phase. Niggling S&R issues can be prevented by tight manufacturing process control that ensures design tolerances on component and subsystem assembly. Despite a stellar structural design, poor quality control can result in poor S&R performance. As a preventive measure, felt tapes are routinely employed at known S&R 'hot spots' in the best of luxury models. Luxury vehicle manufacturing lines can be studied and cost-effective measures adopted even for economy vehicles. Online inspection of subsystems contributing highly to S&R prior to installation in vehicles on the assembly line could be an invaluable S&R detection tool. Rusen, et al., have designed an apparatus for inspecting instrument panels and steering column assemblies online before installation in vehicles.[13]

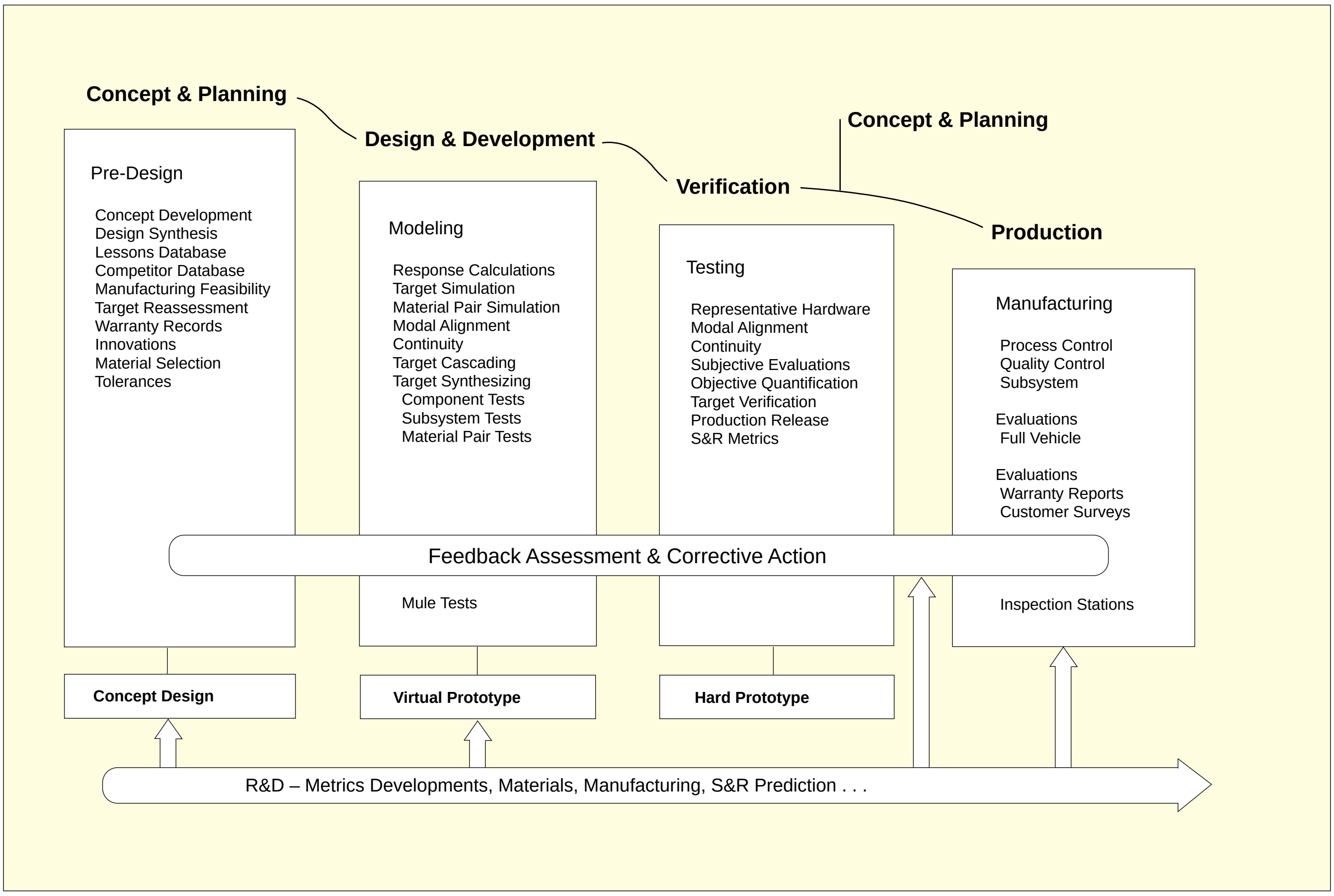

Figure 7. Integrated S&R prevention strategy.

Similar inspection stations for seats, door systems, center consoles can be developed. The key is to ensure that such online inspection stations are smart predictors of impending S&R issues and are both time and cost effective. With the modular assembly concept gaining in popularity, such stations will be common in assembly plants over the next decade. Another factor favorable to this concept is the current OEM push for total supplier test capability and S&R responsibility. In such a scenario, inspection stations could be used by the OEMs as a filter for poorly assembled subsystems. Extending the concept of the inspection stations further, all vehicles out of the plant could be subjected to a final S&R certification with a simple test station based on the lines of a simplified four-post simulator. If an effective S&R metric index is developed, a single noise measurement at the driver location could indicate the S&R performance of the vehicle under a typical input profile. Uchida and Ueda[14] have published a non-stationary signal analysis procedure for detection of rattles. Once the S&R are detected, they need to be quantified. At least one attempt at formulating such a metric for rattles is published by Weisch, et al.[15] An end-of-the-line total vehicle S&R inspection station must again be cost and time effective, especially for high-volume production vehicles.

The production process must track the problems reported at the end of the assembly line, customer survey reports, JD Power surveys and warranty claims and adapt to solving S&R issues as quickly as possible.

Role of CAE

The participation of CAE has been called for at various stages in the integrated design strategy. Scarce work has been reported in the CAE modeling area as far as S&R are concerned. Although the physics of the phenomenon have been published earlier, the direct application to S&R problems has only been published very recently. CAE can be used as a big cost and time saving tool by reducing testing needs and can be applied at several levels in the S&R design chain. Firstly, the squeak and rattle phenomena should be modeled in CAE to predict the squeaks and rattles correctly. Secondly, CAE can simulate modal analysis and four-poster/road test simulations on full vehicles and subsystems to deploy targets and possibly cascade or synthesize them. Accurate CAE models can evolve to include the chemical compositions and surface treatment properties in a material pair slip stick simulation in the presence of multiple environments. This can reveal the susceptibility of the material pair to S&R. Prediction of such issues can aid the selection of the best possible materials at the earliest stages of design. Shaw, et al.,[16] have published a CAE methodology for reducing rattle in structural components. Her, et al.,[17,18,19] have talked extensively of the finite element analysis (FEA) approach as applicable to S&R prevention. Grosh, et al.,[20] have demonstrated the use of commercially available FEA (NASTRAN, ABAQUS) and flexible body dynamics software (ADAMS, DADS) for rattle prediction. Figure 8 illustrates the commonly adopted CAE approach to S&R based on the one proposed by Her, et al.[18] The pros and cons of the two techniques require them to be used in tandem on a hybrid platform. While the simple approach provides physical insight into the fundamentals of S&R phenomena, the direct FEA approach is more attractive due to its practicality. The large data mass and the computing requirements that the direct approach demands are quite easily met with continuous advancements in computer science. Soine, et al.,[21] have proposed a design assessment tool for rattle performance based on the threshold-of-motion criteria. CAE can also possibly be used to provide accurate and optimum tolerances for components and subassemblies. Thus, CAE has the potential to provide a complete virtual proving ground that could relegate testing to a validation exercise.

Conclusions

Squeaks and rattles are very difficult to detect in the pres-

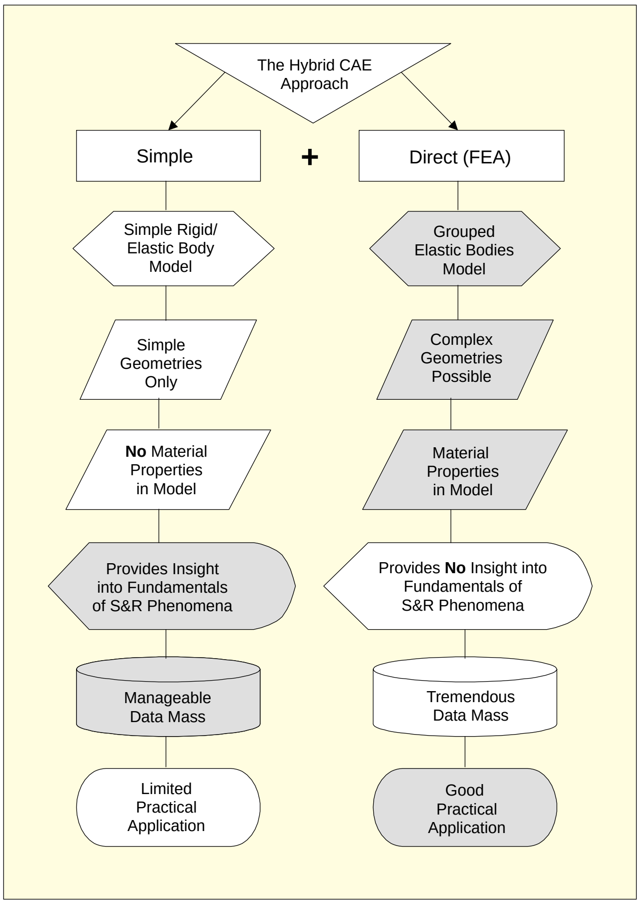

Figure 8. The hybrid CAE approach to S&R modeling.

ence of background noise. Novel signal analysis schemes in the time-frequency domain are being increasingly adopted.[14] In the future, squeaks and rattles could possibly be extracted using sound recognition schemes from a preestablished database of S&R noises, utilizing neural networks. The need for a robust metric for S&R evaluations has been evident for some time. Because of the stochastic nature of S&R, the formulation of one has not been easily possible. Genuit[22] introduced the concept of the relative approach to evaluate S&R but further work is needed to develop an effective S&R metric.

The benefits of subsystem and full vehicle inspection stations have been outlined before. Such stations can filter out poorly assembled components from reaching the final product and save considerably on warranty repair costs. Some work is ongoing in this area. For their large-scale acceptance on assembly lines, the inspection stations of the future must concentrate on prediction accuracy, time and cost effectiveness. They must prove their worth through warranty cost savings.

While determining structural integrity, the importance of mode shape continuity has been emphasized by Nolan, et al.,[1] and Kavarana, et al.[4] Structural continuity is critical for S&R prevention. Common characteristics of vehicles that are subjectively rated as having good NVH properties are the continuity and global character of their mode shapes.[1] However, a means of quantifying the continuity of mode shapes still needs to be established. Additionally, the fallacy of targets solely based on resonant frequencies has been discussed before. The response-based target setting approach has been detailed by the authors.[4] The need exists to identify the additional parameters necessary to complement the traditional frequency based target setting, supplement the response-based technique and to quantify mode shape continuity. The authors further intend to carry out research in this area.

Presently, CAE is in its infancy with respect to the S&R field but has unlimited potential for the future of S&R. Work is currently ongoing for adopting the response based approach[4] through CAE. Future work will also include modeling the material pair friction phenomenon. Someday, CAE will incorporate S&R prediction tools that provide real time S&R audio at the workstation.

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