Applied Acoustics 73 (2012) 265–275

Contents lists available at SciVerse ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Technical Note

End-of-line inspection for annoying noises in automobiles: Trends and perspectives

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ARTICLE INFO

Article history:
Received 18 March 2010
Received in revised form 23 June 2011
Accepted 27 June 2011
Available online 17 September 2011

Keywords:
Annoying noises
Inspection
Rattles
Acoustic imaging
Beamforming
Automobile

ABSTRACT

Annoying noises such as buzzes, squeaks and rattles (BSRs) are particularly important to the perception of quality in complex manufactured durable goods such as automobiles. These products represent significant expenditures to the average consumer and are expected to provide safe and reliable performance for many years. Consumers use sensory responses such as sound as a gauge of the product quality; hence it is important to provide a product that does not exhibit BSRs. Manufacturers have traditionally relied on human auditors to conduct product acceptance testing for BSRs at the end of the assembly line.

This paper provides state-of-the art review and future perspectives for the current processes of BSR inspection used by automobile manufacturers in the United States. The requirements for BSR inspection methodologies are presented in terms of three functional areas: detection, classification and localization. While human auditors provide an effective combination of these functions, they are limited in their performance. A critical perspective analysis of the current process, in terms of these three areas, reveals significant issues with repeatability and reproducibility of inspection results when human auditors are used. These issues demonstrate a clear need for more objective methods of inspection for annoying noises at the end of the assembly line. A number of new technology trends, particularly in the fields of psychoacoustic applications and acoustic imaging hold some promise in addressing the limitations of human auditors. These are discussed in the context of requirements for an ideal inspection system which is capable of providing all three capabilities. There is research being conducted in each of the three functional areas, and in some cases at the intersection of two out of the three areas, further work is needed in developing a methodology combining these functionalities.

1. Introduction

The automobile is one of the most expensive and complex purchases made by an individual consumer and is the subject of intense scrutiny prior to purchase. As performance and reliability perceptions of available products converge, issues of craftsmanship such as sound quality become increasingly important as a customer requirement. Surveys show annoying noises such as buzzes, squeaks and rattles (BSRs) play a significant role in creating a negative perception of durability and craftsmanship [1] in automobiles, making up 6.5% of all vehicle issues at three months in service [2]. The prevalence of BSRs as a major quality issue is expected to increase as electric vehicles enter the market. Electric vehicles have significantly less powertrain sound than their IC engine counterparts, hence less masking of these annoying noises.

While the need to control BSRs is increasing, they remain one of the most challenging of quality control issues. The risk of creating buzzes, squeaks and rattles in product manufacturing is proportional to the product complexity. Products such as automobiles, with thousands of individual parts, are susceptible to large numbers of potential BSR sources including: missed assembly operations, incoming-component quality, adjacent-material incompatibilities and dimensional control issues. Many of the sources of BSRs are directly related to manufacturing issues; hence the automotive industry focuses of BSR evaluation at the end of the assembly line. By conducting the inspection on finished products, the scope of the inspection is large. Each produced unit has the potential for having multiple annoying noise defects. In addition to their prevalence in complex products, BSRs present in unpredictable characteristics and locations. This adds to the challenge in their control.

With the increasing emphasis on craftsmanship as a competitive attribute, manufacturers are faced with re-evaluating their current methods of sound quality inspection using human auditors. The feasibility of objective inspection for BSRs in automobiles not only enables the elimination of highly variable human auditors, but also allows for the objective classification and management of BSR defects.

This paper provides some recent developments and trends in the fields of psychoacoustics and acoustic imaging that have the potential to make objective inspection for BSRs in automobile assembly plants possible. The first section discusses the current

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doi:10.1016/j.apacoust.2011.06.019

end-of-line inspection process for BSRs seen at most assembly plants and the requirements for the process described in terms of three functional areas: detection, localization and classification. Secondly, a critical analysis is provided of the effectiveness of the current process in terms of these basic functional requirements. Finally, it concludes with an ideal automated inspection system using spherical beamforming technology for its potential applicability to the BSR inspection processes, and resulting benefits.

1.1. Requirements for a BSR inspection system

The process for inspecting finished automobiles for annoying noises such as buzzes squeaks and rattles is a particularly challenging acoustic application due to the thousands of possible combinations of defect types, locations and severities. This challenge may also be experienced by manufacturers of other large complex assemblies in which sound quality is an important customer requirement (i.e. airplane cabins, train cars and to some extent construction equipment). The automobile is the most challenging though because in addition to the complexity, there is a high production flow rate coupled with an end product which will be purchased directly by individual consumers. Ideally, a BSR inspection system should be able to identify and locate any of the thousands of potential combinations of defect types and severities possible in a particular assembly. Any BSR inspection system must be able to provide consistent performance in three functional areas: detection, localization and classification.

1.1.1. Detection

Detection of BSRs is complicated by their wide-ranging characteristics. The most comprehensive discussion of the characteristics of buzzes, squeaks and rattles was provided in a paper by Kavarana and Rediers [3]. The transience of BSR sounds, makes them unpredictable and hard to measure. A rattle that may be clearly heard on one road surface, may not be evident on another. In addition to the variation in the BSR sound sources themselves, the environment in which they are evaluated also adds to the challenge. BSR artifacts are often very low signal to noise ratio (SNR) events which are masked by the sound of operating noises in the vehicle cabin. The challenge is that even though the events have low SNR, the sounds are distinctive and easily detected by consumers. This challenge was described in research by Cerrato, where rattle and squeak data traces from a vehicle cabin were combined with data for background noise vehicle noise. The squeak and rattle defects were indistinguishable from the background noise in the combined data trace, yet when listening to the combined data in the audio file, the defects were obvious [7].

1.1.2. Localization

Localization is particularly important to inspection for BSRs for two reasons, first the root cause of the defect must be found quickly and documented to enable upstream control of the processes that created it; secondly, the repairs must be completed as quickly as possible on the affected vehicles. Requirements for localization are often described by plant management personnel in terms of distance between the actual source input to the cabin location and the target location provided by the system. Our interviews with plant quality personnel return an average requirement of ±15 cm maximum error for any source in the vehicle cabin. In order to compare the performance of systems in a variety of vehicle cabin configurations, this requirement may be better expressed as an angular error. Consider a passenger vehicle with a large volume cabin, such as a minivan, where the distance between the sensor and the potential defect site may be as large as 220 cm. If for instance we have a rattle in a rear hatch latch mechanism at a distance of 220 cm from the auditor driving the vehicle, and is identified as emanating from the D-pillar 15 cm away, the angular error (E_A) would be,

$$E_A = \arctan(15\ \text{cm}/220\ \text{cm}) = 3.9^\circ. \quad (1)$$

The angular requirement for accuracy is relaxed (gets larger) as the distance to the furthest point in the vehicle decreases (smaller cabin space). Therefore, if our vehicle was a small hatchback sedan with the same defect at a distance of 150 cm, that 15 cm error would represent an angular error of 5.7°.

1.1.3. Classification

Classification performance is harder to specify as the definitions of acceptable versus unacceptable BSR characteristics are vague and changeable in practice. Annoying noises are extremely difficult to quantify in terms of severity for complex assemblies, hence most target development for vehicle BSR levels is subjective. The reality is that engineering or plant quality personnel must estimate the customer response to the severity of acoustic defects and act as the "voice of the customer" when approving assemblies for shipment. This is a delicate balancing act of cost and quality is played out on a daily basis in most assembly plants. The inspection system must be able to classify the events found such that they agree with the assessments of engineering and/or plant management in a consistent manner.

A final consideration is the robustness and "fitness for use" of the inspection system. Any inspection system used in a plant environment must have a reasonable cycle time and be able to work in the diverse environment of the plant. The environment of an automotive assembly plant is often dusty, with the possibility of airborne contaminants such as grease. Air temperatures vary widely as the end-of-line processes are often positioned close to the exit from the plant and experience outside temperature and humidity. Finally, the plant environment is one of rough handling, so fragile equipment is not feasible. The following section describes the current process used by automotive assembly plant to inspect completed full vehicles for BSR defects.

2. Methods for annoying noise (BSR) inspection at automotive assembly plants

Traditionally, quality control for annoying noises has been done using human auditors. Our recent study of the methods used by manufacturers participating in the USCAR Consortium, shows the traditional processes continue to be used. In this process, an auditor listens for objectionable sounds while a product is put through a standard excitation cycle. In the case of full automobiles, this may be a test track with excitation events such as potholes, washboard roads or Belgian blocks; or alternatively excitation may be done using a four-post shaker. The common feature though is the human detection, localization and classification of audible defects. Fig. 1 shows a flowchart of a traditional BSR inspection process used at most automobile assembly plants. The heavy black line indicates the main flow of defective units through a time-consuming two-step audit process.

As the vehicles exit the final assembly line, a sample is selected for inspection by a human auditor. The auditor prepares the vehicle for inspection by completing a brief checklist including: radio off, HVAC fan speed to low and windows up. Once this is done, the auditor drives the vehicle to the test track and proceeds with the evaluation. The auditor usually notes the occurrence of BSR defects and their approximate locations while navigating the course, or simply by memorizing the events and recording them at the end of the evaluation in text form. The auditor must also make an immediate decision as to whether the BSRS event is severe enough to warrant repair. Most auditors are given some basic training on