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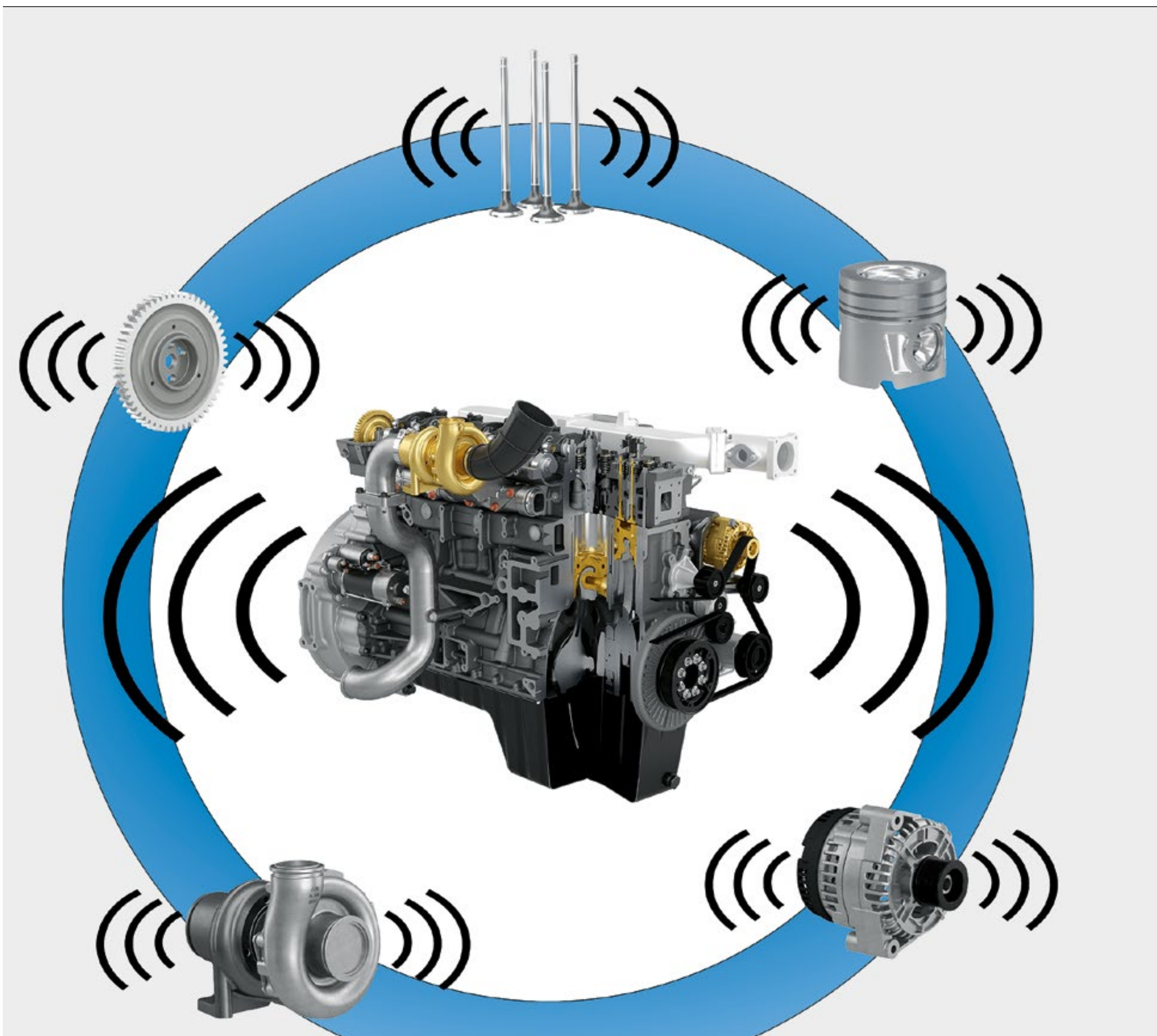
Allocation and Evaluation of Engine Noise Components

The perceived noise quality of internal combustion engines is significantly influenced by the occurrence and characteristics of individual disturbing noise components. Within the scope of an FVV research project, a methodology was developed at the Institute of Internal Combustion Engines of the RWTH Aachen University that enables the extraction of individually audible engine component noises from a total engine noise and the automatic quantification of the annoyance level of these components. In addition, the methodology allows the synthesis of a newly weighted total engine noise from the separated noise components for target value definition.



1 MOTIVATION

When purchasing a passenger car, the customer's choice is increasingly influenced not only by objective criteria but also by the quality-based impression of the vehicle. The perceived noise quality of the powertrain plays a central role in the purchase process. The occurrence and the characteristics of individual disturbing noises which are to be optimized during vehicle development have a significant negative effect on the perceived noise quality. Prerequisites for an effective acoustic optimization are the identification of disturbing noises within the total engine noise as well as the allocation of these noises to the causing engine components or processes.

In an FVV research project, a method for software-aided analysis and evaluation of the noise quality of engine noise components has been developed. This method allows the automatic identification of noise causes in combustion engines and the evaluation of the potential for improvement. Conventional evaluation methods are limited due to the cross-interference of engine noise components [1]. Hence, subjective assessments of impulsive noises of for example an injector can be influenced negatively by tonal noise segments of for example an exhaust gas turbocharger. Therefore, this research project is based on methodologies for the extraction of tonal and impulsive disturbing noises which have been developed as part of the research projects Objektivierung Subjektiver Beurteilungen II (OSB II) (Objectification of Subjective Evaluations II) and Motorgeräuschkomponenten (MGK) (Engine Noise Components) [1, 2].

A crucial innovation is that the disturbing noises are subsequently re-grouped so that individual engine noise components as for example a high-pressure pump or an exhaust gas turbocharger can be listened to and their annoyance is evaluated. The methodologies for the annoyance evaluation were adopted from the OSB II and MGK projects. Another innovation is the automatic allocation of the grouped noises to the emitting engine components or processes, respectively. Based upon this, the objective assessment of the annoyance of individual engine components and processes allows an effective evaluation of acoustic optimization measures. Furthermore, it is possible to define a new target noise by a newly weighted superimposition of the engine noise components. This allows the subjective quantification of the actual degree of the required acoustic optimization.

TABLE 1 Examined engine components (© RWTH Aachen University)

Impulsive		Tonal
Combustion	Fuel injection pump (FIP)	Turbocharger
Injector	Valve	Alternator
Wastegate	Gear	Oil pump
Piston slap	–	Timing drive
–	–	Gear

2 APPROACH

Beginning with the decomposition of the monaural sound pressure measurement and the subsequent grouping into engine noise components, selected characteristics are calculated and allocated to an engine component or process by a classifier. First, a noise data bank with selected engine noise components has to be created, and characteristic qualities have to be defined. Then a suitable classifier is selected and trained.

At the beginning of the research project, the engine components to be examined were selected, **TABLE 1**. According to the conspicuous noises, the engine components are divided into the noise groups impulsive and tonal. The data bank created as part of this research project is based on component measurements and test bench measurements.

3 TONAL CHARACTERISTICS

The transmission ratios for alternator and oil pump have been measured in this research to facilitate the classification of tonal noises with a mid-frequency that is proportional to the engine speed. The analysis of these data shows that the transmission ratio of the oil pump is typically near one, and that of the alternator typically between two and three. The clear separation of these ranges demonstrates that the transmission ratio is suitable as a characteristic for the separation of the first harmonic. Additional studies have shown that the coefficient of determination of the linear regression of the sound pressure level above the logarithmic speed can be used to also separate the second harmonic of the oil pump noise from the first harmonic of the alternator noise. In contrast to the timing drive, the tonally conspicuous engine orders of the alternator noises and the oil pump noise are typically not integers. Due to the design, the order of excitation of the drive pinion of a timing drive is always an integer and typically falls within a value range between 19th and 24th engine order. Therefore, the calculated engine order can be used as a characteristic as well. Within the scope of this research, only the exhaust gas turbocharger is examined under tonal noises with an engine-speed-independent mid-frequency.

4 IMPULSIVE CHARACTERISTICS

It is well known that the characteristics of the frequency spectrum are representative for an engine component. Therefore, a method has been developed to detect the characteristic areas in the averaged amplitude spectrum. **FIGURE 1** shows the application of the method to the amplitude spectrum of an injector and a valve noise. The amplitude spectrum is characterized by a global frequency center as well as local frequency centers with corresponding area widths. The

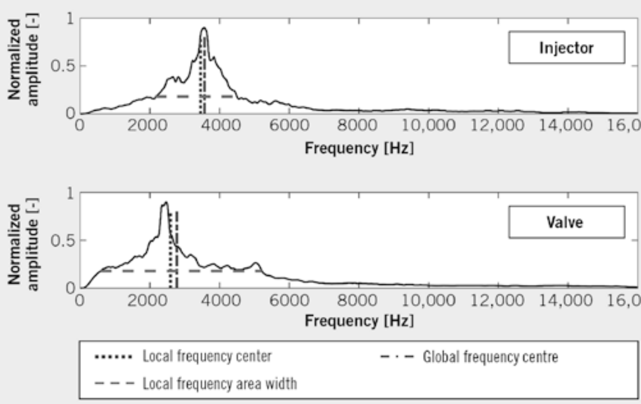


FIGURE 1 Detection of characteristic frequency ranges in the amplitude spectrum (© RWTH Aachen University)

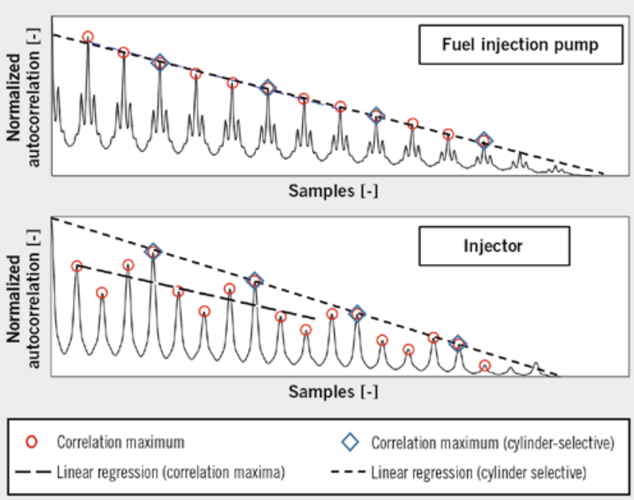


FIGURE 2 Autocorrelation function of the envelope of an airborne sound signal (© RWTH Aachen University)

global frequency center evaluates the energy distribution. The local frequency centers describe prominent individual areas. With the help of the developed methodology, the broadband frequency characteristics of valve ticking or the narrow band frequency excitation of the injector can be quantified by the local frequency area width.

Within the scope of this work it was also shown that the location dependency of the noise origination of a noise component can be detected in a stable manner by the autocorrelation function of the envelope of the sound pressure. **FIGURE 2** shows the autocorrelation function for the noise of a high-pressure pump compared to the injector noise of a four-cylinder engine. It is clear that the correlation maxima for the autocorrelation function of the high-pressure pump decrease linearly over time. The autocorrelation function for the injector however shows the location- and component-dependent sound radiation. This is assessed by the square sum of all errors for the linearization of all correlation maxima. Further characteristics used for classification have been determined by an optimization of the classification rating.

5 EXTRACTION AND CLASSIFICATION OF TONALLY CONSPICUOUS NOISE EFFECTS

The method developed in [1] for the detection of tonal noise components is based on the reduction of the short-term spectrum to a binary image. Tonal noises are detected by referencing the energy of the examined frequency area to the energy of the corresponding third. The tonality spectrum created is converted into a binary image, the so-called tonality mask, by applying a threshold value. Then imaging algorithms are used for the extraction of the tonal noises. The image processing allows the detection of the tonal components as closed line structures in the image. After the removal of the interference signal, the tonal noise components are divided into engine speed dependent or independent depending on the proportionality of the mid-frequency to the crankshaft speed, **FIGURE 3**.

6 EXTRACTION AND CLASSIFICATION OF IMPULSIVELY CONSPICUOUS NOISE EFFECTS

For the detection of impulsive engine noise components, the Non-negative Matrix Factorisation (NNMF) is coupled with the k-means algorithm. The NNMF is applied to the magnitude spectrum of the short-term spectrum. It identifies recurring frequency patterns and generates partial noises from these patterns. These are then grouped into engine noise components with the k-means algorithm based on the time correlation of the envelope. The algorithm is modelled as a maximization problem and automatically calculates the number of engine noise components depending on the silhouette coefficient. **FIGURE 4** shows the application of the methodology. In the short-term spectrum, a high-pressure pump (HPP) and an injector can be identified. As an important addition, the algorithm checks the separation quality independently and, in case of insufficient separation, subsequently applies the Non-negative Matrix Factor Deconvolution (NNMFD). This can happen when the engine components contained in the airborne sound signal demonstrate very similar frequency spectra. Directly impulsive engine noise components are then separated from the total noise using the NNMFD, **FIGURE 5**.

7 CREATION OF THE CLASSIFIERS

An important scientific innovation apart from the automated extraction of engine noises is the automated allocation to the corresponding engine components. Due to the limited amount of training data for tonal noises, a linear decision tree was designed as a classifier. Based on the presented characteristics, the calculated engine order is used for the classification of the crankshaft-dependent tonal noise phenomena and the estimated transmission ratio is used for the direct classification. As the calculation of the transmission ratio does not allow a unique allocation, the frequency distribution of the transmission ratio as well as the coefficient of determination of the level regression are used as a measure of quality assessment for classification. Accordingly, a probability is assigned to the result of the allocation. The decision tree for the noise phenomena of the exhaust gas turbocharger correspondingly structures frequency areas [3]. For the classification of impulsive engine noise components, a naive Bayes classifier was trained. The achieved classification rating is 81 %. The classifier has the advantage that it indicates probabilities for the allo-

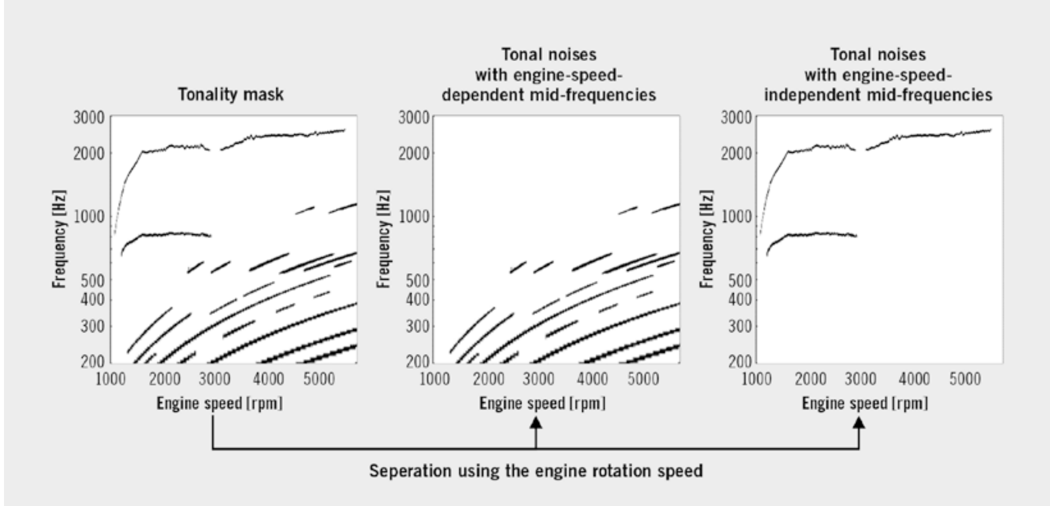


FIGURE 3 Division of tonal noises (© RWTH Aachen University)

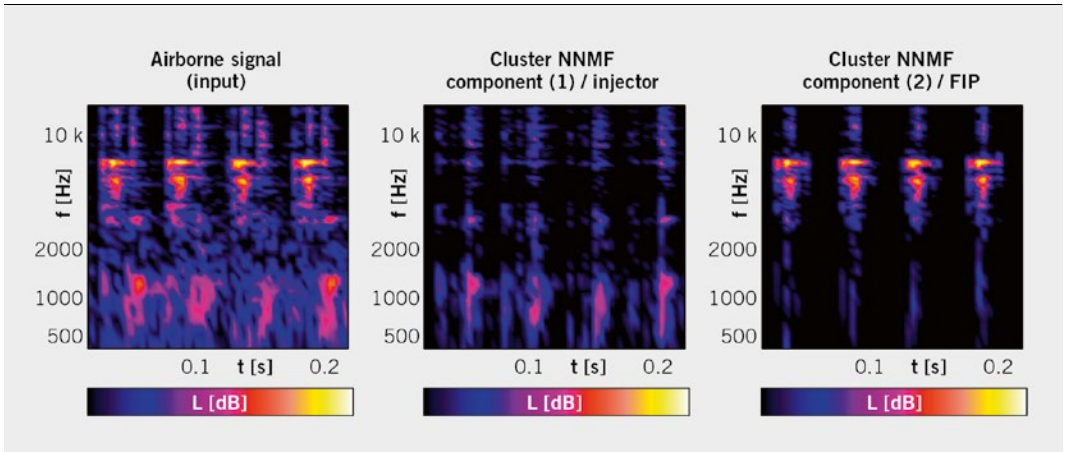


FIGURE 4 Noise extraction of impulsive disturbing noises (© RWTH Aachen University)

cation and that the user can analyse the results further in case of doubt [4]. Furthermore, the developed methodology allows an extension of the data base as well as the training of the naive Bayes classifier for individual applications.

8 SUMMARY

Within the framework of the FVV research project Motorgeräuschkomponenten II (Engine Noise Components II), a methodology was developed which allows the automated decomposition of an overall engine noise into individual audible engine noise components as well as the automated allocation of the noise to the emitting engine components (for example injector or exhaust gas turbocharger) or processes (combustion). In combination with the automated calculation of the annoyance, acoustic optimization measures can be evaluated effectively. Moreover, the degree of the required acoustic optimization can be quantified by the synthesis of a newly weighted target noise.

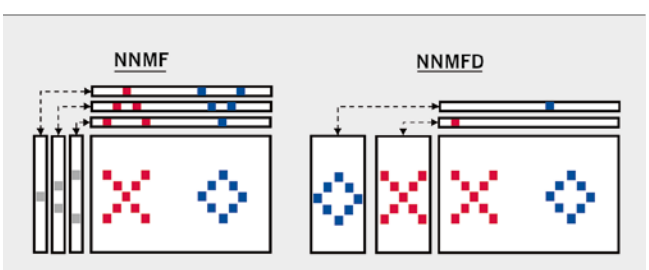


FIGURE 5 NNMF and NNMFD (© RWTH Aachen University)

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THANKS

This report is the scientific result of a research task carried out by the Research Association for Internal Combustion Engines (Forschungsvereinigung Verbrennungskraftmaschinen e. V., FVV) under number 1207 and worked on at the Chair of Internal Combustion Engines at RWTH Aachen University under the direction of Prof. Dr.-Ing. Stefan Pischinger. The work was carried out by the Federal Ministry of Economic Affairs and Energy (BMWi) through the Federation of Industrial Research Associations e. V. (AiF no. 18834 N/1). The FVV thanks Prof. Pischinger and the scientific editor, Christian Schumann, M. Sc. for the implementation of the project as well as the BMWi and the AiF for the financial support. The project was accompanied by a working group of the FVV under the leadership of Dr. Michael Fischer, Robert Bosch GmbH. This working group expresses its gratitude to the FVV for the great support.