Main topic:

Noise, Vibration and Friction
Sustainable solutions, inspired by ecology and economy

Virtual acoustic design of engines  ■  NVH Optimisation
Friction reduction  ■  New NVH tools and requirements

With contributions of:
Today, automotive engineers are facing new challenges, among others the conflict between good NVH performance and lightweight targets.

Reducing mechanical losses yields a significant contribution to reducing the fuel consumption. Therefore, VIRTUAL VEHICLE investigates all important sources of friction in the drivetrain on the FRIDA friction test bench.

Automotive industry is asking for new methodologies to characterize the acoustic emissions of electric motors. VIRTUAL VEHICLE develops an experimental methodology based on cylindrical Nearfield Acoustical Holography.

VIRTUAL VEHICLE has developed new methods for reducing low-frequency drive train vibrations taking a parallel hybrid design as an example.

VIRTUAL VEHICLE operates comprehensive test facilities designed to investigate the acoustic properties of vehicle components such as the engine and drivetrain.

Three ongoing Marie Curie Action projects at VIRTUAL VEHICLE focus on training of PhD students in relevant NVH topics of automotive vehicle development.

At VIRTUAL VEHICLE a 1D simulation tool has been developed that simulates the acoustic transmission behavior of the intake and exhaust gas system and thus shows the acoustic properties at the early design stage.
Research and development in the fields of noise, vibration, harshness and friction are of crucial importance for automotive industry. In the last decade NVH has become part of a multidisciplinary design optimisation process, also boosting the collaboration between the different research areas of the VIRTUAL VEHICLE.

In response to the progressively more stringent environmental regulations in automotive industry, OEMs and their suppliers and partners have significantly increased their efforts towards eco-friendly vehicle development during the last years. Nevertheless, these innovations – regardless if under development or already implemented in series-production vehicles – shall not deteriorate the vehicle NVH quality. In order to maintain the competitive edge, the noise emission and passenger comfort levels must meet or even exceed the customer expectations also for the next generation of eco-friendly vehicles.

Traditional challenges meet new challenges

Creative solutions for the conflicting demands of lightweight design and excellent NVH has become of central importance, involving novel research in areas such as aeroacoustics, composite materials and full vehicle modelling. In addition, interactive effects of hybrid and electric drives, sophisticated turbo-charging concepts, downsizing strategies and friction reduction must be accounted for.

In April this year, the EU parliament voted in favour of a Commission proposal to decrease vehicle noise in road traffic until 2026. A decrease of noise limit values for passenger cars, vans, buses and coaches by 4 dB(A) and for trucks by 3 dB(A) are supposed to reduce vehicle noise nuisance by some 25%. This will require intensive R&D efforts in fields such as tire acoustics, acoustic insulation materials as well as intake and exhaust acoustics.

Step by step to a solution

In close cooperation with leading partners in science and industry, e.g. BMW, AVL, MAN or TU Graz and KTH, researchers at VIRTUAL VEHICLE develop efficient and reliable simulation and validation methods and support the applicability of NVH virtual prototyping.

Just in time for our 8th ISNVH Congress, this edition presents several research highlights: With new prediction methods for the acoustics of fiber reinforced plastics and efficient trim characterization, relevant contributions to reliable NVH material modeling are provided. A sophisticated model for the chain drive dynamics allows enhanced system understanding. Extensive experimental facilities - from acoustic engine test rig to friction dynamometer - are enablers for solving R&D challenges at VIRTUAL VEHICLE.

In this magazine we also feature EU projects in the Marie Curie Actions, where VIRTUAL VEHICLE has been successful in providing training to PhD students that goes far beyond university education. We asked top-class partners from industry on innovative NVH solutions and on future trends in engine development.

We hope you enjoy the various contributions in this edition.
Due to factors such as the enormous economic growth of the BRICS countries (Brazil, Russia, India, China and South Africa), the global demand for energy, and primarily for fossil fuels, is increasing dramatically. As a result, energy is becoming more and more expensive, which also increases the costs of mobility for both business and private transportation. On top of this, environmental sustainability has become a priority and fuel efficiency and exhaust emissions have consequently moved to the top of the agenda. This poses enormous and frequently conflicting challenges to the OEMs who must assure low emissions and fuel efficiency without jeopardizing safety, comfort, fun-to-drive and durability at an affordable and competitive price. In order to assist automotive industry as good as possible in this difficult task Area NVH & Friction at VIRTUAL VEHICLE focuses on the following topics:

• NVH materials & technology
• Vehicle noise reduction
• Friction loss & vibration reduction
• Flow acoustics
• NVH Testing & measurement

NVH materials & technology

New materials with enhanced characteristics are enabling a further improvement of the NVH properties of modern vehicle concepts. Area NVH & Friction has for instance conducted detailed experimental and numerical investigations with regard to the acoustic behavior of cellular metal foams. The microscopic material behavior is modeled with the multiscale method, in order to calculate the complete component efficiently.

Currently, research and development is focusing strongly on multi-material applications for lightweight bodies combining aluminum, magnesium, high-strength steels, CFRP and organic sheets. Such materials will help to meet future requirements for lower weight, more safety, increased strength and increased comfort in terms of acoustics and vibration.

From an acoustic point of view, lightweight also means easily excitable and therefore noisy and loud. However, the customer is not prepared to sacrifice today’s driving comfort. In order to design an improved lightweight vehicle body with suitable vibration and acoustics properties, the structural dynamics, vibrating behavior, sound transmission behavior and radiating behavior have to be examined in detail in order to meet the client expectations with regard to comfort.

New simulation procedures are necessary for the virtual design of lightweight bodies in terms of engineering strength, crashworthiness and vibration behavior.
The modeling of multi-layered composite materials in the acoustic frequency range still poses a real challenge. Numerical results shall not only guarantee sufficient accuracy but modelling efforts and calculation times must be compatible with the industrial processes in the automotive industry. Research work also focuses on the non-destructive crack detection, crack localization and damage detection of fiber reinforced plastics via acoustic measurement engineering.

Downsizing – a major challenge for flow acoustics

Downsizing means reducing mass and engine displacement while maintaining performance levels. This can be realized, for example, by a reduction of the number of cylinders and by forced induction. Reducing the number of cylinders and optimizing combustion processes in combination with forced induction change the NVH behavior dramatically. New methods and technologies are necessary in order to improve downsizing concepts, in particular with regard to vibration comfort and acoustic behavior.

One important aspect related to downsizing is the acoustics of intake and exhaust systems. One of the core competences of Area NVH & Friction is the precise prediction of the orifice noise of turbo-charged engines, based on improved simulation methods for the individual components (e.g. turbocharger, muffler, after-treatment of exhaust gases). To this end, all of the relevant disciplines are available in the form of networked experts.

Friction reduction in engines and transmissions

Increasingly stringent exhaust regulations are forcing OEMs to continuously increase the efficiency of their vehicles. In modern combustion engines, approximately 70% of the fuel energy is lost through heat (60%) and friction (10%). Only about 30% of the provided fuel energy is available as usable power at the crankshaft. Since the usable power is further reduced by the transmission, wheel bearing, tires, etc. in the end, only 20-25% of the provided fuel energy is used for propulsion. In order to effectively reduce friction in the powertrain, simulation methods are required that can enable system-optimization measures in the early development phase. To this end, efficient and reliable calculation methods are being developed at VIRTUAL VEHICLE, in order to meet industry demands.

The various validated methods for the calculation of friction in the piston assembly, in the crankshaft bearings, in the valve train, in the timing drive and the transmission are the result of a large number of industry-related research projects and strategic projects that have been carried out in the last years. The engine friction test bench FRIDA (see page 10) developed at VIRTUAL VEHICLE has been the last step in this process and positions VIRTUAL VEHICLE in the front line of the research done in this field of tribology. Through measurement-calculation comparison, the test bench offers the possibility to validate newly developed calculation methods, to study material combinations and coatings and to understand full-system interactions. The comprehensive understanding of tribological mechanisms forms the basis for further research activities geared towards the reduction of friction in combustion engines.

NVH simulation and measurement of the powertrain

There is still a great potential to improve conventional propulsion concepts in order to fulfill the high demands regarding fuel consumption and emissions. Virtual development methods can contribute significantly to this improvement by enabling the modeling of future product requirements in a faster, yet cheaper manner. To achieve this, however, the powertrain must be taken into consideration more strongly in the early stages of development without losing sight of the full-vehicle requirements. Currently, rapidly advancing developments in the field of electrification of the powertrain pose new challenges due to increased complexity, a greater amount of variants, and the demand for more interdisciplinarity and improved consistency in the development process. To this end, VIRTUAL VEHICLE supports OEMs and suppliers with application and industry oriented research in the field of NVH and friction.

Test benches for the support of vehicle development

VIRTUAL VEHICLE operates numerous acoustic test benches, which are described in more detail on page 28. The engine test bench is located in a full anechoic chamber for measuring vibrations, noise emission and exhaust emissions from combustion engines in operation. The powertrain test bench is located in a semi-anechoic chamber, in which the vibrations and noise emission of entire drivelines can be measured. In the modal analysis test bench, the natural frequencies and eigen-modes of complex structures (e.g. the vehicle body) can be measured to be used for model updating. At the friction test bench, the engine friction can be determined, as well as the contributions of individual components (piston, bearing, etc.) to the overall friction. The Sound Brick is a reverberation chamber that is similar to a vehicle, in which material properties (e.g. sound insulation properties and absorption coefficients) can be measured.

This edition of the VVM presents selected research activities of Area NVH & Friction and shows how new methods of simulation and experimental investigation are being pursued based on existing experience from automotive and rail technologies.

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Plastic components are more and more used in modern vehicles. Besides conventional plastics, fiber reinforced plastics show a high potential for lightweight construction and currently strongly expand into structural parts. VIRTUAL VEHICLE investigated requirements for the acoustic simulation of structural parts in the powertrain made of fiber reinforced plastics.

Carbon fiber reinforced plastics weigh around 60% less than steel and about 30% less than aluminum. This high potential for lightweight design and hence for CO₂ reduction is the reason why automotive industry puts so much effort in a cost-effective production suitable for high quantities.

The acoustics of fiber reinforced plastics replacing metal powertrain parts is of high interest, due to the fact that lightweight structures show disadvantages in the acoustic mass damping effect. In addition, the most effective way concerning costs and weight to reduce unwanted noise shares is directly at or near the source. In case of the powertrain this means for example to directly reduce the noise emission of the engine by optimizing covers and general structures primarily before increasing the airborne sound transmission by adding additional damping material to the firewall.

Challenges for acoustic simulation of fiber reinforced plastics

Fiber reinforced plastics show a strongly anisotropic behavior compared to metals. It is mainly caused by the material properties, composition and the manufacturing process. In Fig. 1 a cross section through a material probe is given, manufactured by injection-molding. It shows a typical composition in three layers consisting of two boundary layers with a fiber direction parallel to the border as well as in flow direction of the melt and an intermediate layer with orthogonal fiber direction. Averaging the material properties over the whole thickness results in a higher E-modulus in the main fiber direction, this corresponds with the longitudinal mold flow direction. In addition, also the material damping shows a directional property. The highest damping occurs in a direction rotated about 45° to the main stiffness direction.

Commercial FE-software tools already include elements for an orthotropic material definition, but still combined with damping approaches not being able to introduce a damping directivity.

Finite Element and Multi Body Simulation

VIRTUAL VEHICLE investigates the requirements for the Finite Element (FE) and Multi-Body (MB) simulation of fiber reinforced plastics based on plate probes (short glass fiber reinforced polypropylene with 40% glassfiber content). Therefore, in the simulation different homogenizations and damping approaches available in FE and MB simulation code were compared to measurements. For the homogenization, the whole plate thickness and a layer-wise approach were compared. The FE-model consists of shell elements, with an orthotropic material definition based on engineering constants. In the FE-simulation, the main vibroacoustic properties including eigenfrequencies, eigenmodes and transfer functions were analyzed and compared to measurements. For the time domain simulation in a MBS software tool the FE-model of the specimen was reduced in complexity. The mode shapes were taken as a basis to take the anisotropic material behavior into account.

In the MB simulation, the damping behavior is introduced via Rayleigh approach.

Acoustic validation measurements

The validation measurements were carried out with the specimen clamped on one end and excited with a volume velocity source or impulse hammer on the other end. The clamped specimen was chosen to compare the measurement.
results with the time domain simulation results in the MB simulation environment. Generally, the MB simulation time domain solution (series of single sinusoidal force excitations) yields very similar results as the FE-simulation in frequency domain.

The comparison of the FE eigenfrequencies shows good correspondence with the measurements, deviations are less than 3% for all modes. The modal assurance criterion (MAC) calculates the correlation of different eigenvectors from simulation and measurement results. The MAC values for the modes up to 700 Hz are in a good consistency. Above 700 Hz, the MAC values are lower but the visible comparison still shows a good congruence, see Fig. 2.

The comparison of transfer functions confirms the good consistency up to around 1000 Hz (see Fig. 3). In this frequency range the specimen mainly behaves like a beam, indicated by a falling mean transfer function characteristic. Above 1000 Hz, the specimen behaves more like a plate. In this frequency range some deviations between measurement and simulation can be observed. Different modeling approaches based on a three layer approach for the plate thickness or different damping approaches (structural and modal damping) do not show a real improvement of the simulation results in this frequency range. These deviations can be traced back to changes in the fiber orientation over the length and width of the test specimen, currently not included in the model.

**Summary**

Researchers at VIRTUAL VEHICLE investigated the vibroacoustic behavior of fiber reinforced plastics experimentally and developed an efficient method to simulate their behavior. This method has been successfully applied for simplified components. It can be seen as a relevant contribution to predict lightweight acoustics in an early vehicle design phase.

Based on the investigations it could be shown that the orthotropic material behavior has a significant impact on the structural dynamics and therefore has to be considered in the simulation process.

Expertise established in this field includes homogenization procedures, model complexity reduction methods and approaches how to model the correct damping of fiber reinforced plastics.

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A NOVEL APPROACH FOR TRIM CHARACTERISATION

Automotive industry is more and more driven by the need to offer fuel-efficient and eco-friendly mobility. Today, lightweight design, downsizing of internal combustion engines along with hybridisation of powertrain are the main strategies pursued by the most OEMs in order to increase the vehicle performance and to reduce its fuel consumption and exhaust gas emissions. At the same time, the lightweight design is expected to worsen the air borne insulation performance of future vehicles. Automotive engineers are therefore facing new challenges, namely the conflict between good NVH performance and lightweight targets.

A common strategy to reduce vehicle interior noise consists in the application of sound insulation and absorption materials (see Fig. 1). Lightweight structures, however, show strong interaction with these sound insulation and absorption treatments. In order to optimise the acoustic design of the future road vehicles, an efficient method for accurate description of the structure-trim-cavity interaction in the frequency range up to 2000 Hz is of high importance.

The challenge

When tackling vibro-acoustic problems involving porous materials, a full finite element modelling scheme based on complex material micro-models is typically adopted.

Unfortunately, as far as industrial problems are considered, this state-of-the-art approach leads to very demanding calculations, which today limits its practical application for the low frequency range up to 300 Hz. Moreover, these models typically require a whole set of material parameters describing the vibro-acoustic behaviour of a poro-elastic trim. In practice, these parameters are acquired by highly specific experimental techniques and are therefore very expensive or even not available.

The novel approach

Over the recent years, a consortium of BMW AG, IAC Group GmbH, Microflown Technologies, ESI GmbH and Université de Sherbrooke, Canada, under the lead of VIRTUAL VEHICLE has developed a novel, experimental trim characterisation method to describe the interaction between vehicle structure, trim and cavity (i.e. passenger compartment).

In this research project, VIRTUAL VEHICLE proposed the so called Patch Transfer Function (PTF) [1] as an alternative method to predict the vehicle interior noise. The PTF is a sub-structuring method, which consists in partitioning of the problem into sub-systems and coupling them at their common interfaces via impedance relations (see Figure 2).

First, the full trimmed body (i.e. vehicle structure plus trim) is divided into individual sub-systems: vehicle structure, trim and the passenger compartment air cavity. The interfaces between each sub-system are discretised into a low number of elementary surfaces, called patches, which have typically the size of 20 by 20 cm. For each patch, the complex spatial distribution of sound pressure and particle velocity is averaged resulting in only one quantity - the patch impedance. To predict the behaviour of the full system, the superposition principle is employed. As a result, the PTF approach allows for independent sub-system characterisation.

Where simulation fails, test takes over

One of the main advantages of the approach proposed is its high flexibility with respect to
the acquisition of the impedances at the coupling interfaces. These impedances can be obtained in experimental, numerical and - if applicable - even analytical manner.

This seamless combination of the experimental approach (e.g. for structure or trim) and the numerical approach (e.g. for the cavity) demonstrates the full versatility of this coupling procedure. It allows sub-systems exhibiting low modal density to be modelled by conventional finite element method (FEM), whereas sub-systems, which are already too complex for an FE description to be characterised in experimental manner. As a result, the strengths of both approaches can be fully exploited in one combined procedure.

A fully flexible workflow

Both numerical and experimental sub-system characterisation techniques of the enhanced PTF have been developed and implemented at VIRTUAL VEHICLE [2]. For a numerical determination of interface impedances, a commercial FE package has been employed.

The experimental characterisation relies on the application of an array of pressure and velocity sensors for non-contact surface measurements. Since both the sound pressure and the particle velocity are measured simultaneously, the interface patch impedances can be determined in a very efficient way.

Experimental trim characterisation and validation

In the proposed PTF methodology, the trim material is characterised experimentally. To determine the trim patch impedances, a dedicated test rig has been designed and built at VIRTUAL VEHICLE. It allows for the vibro-acoustic properties of layered trim media to be measured directly without the need of having complex material parameters available. The material data acquired by the test rig is compatible with the PTF description and can be further used in the coupling process in a straightforward way.

The proposed PTF approach has been validated by an appropriate test case. A clamped steel plate has been damped by a layer of porous material and coupled with a rigid rectangular cavity. The test case is represented in Fig. 3.

The individual sub-systems have been characterised separately in experimental, numerical and analytical manner. The PTF method has been applied to predict the behaviour of the full-system. Results obtained inside the acoustic cavity by means of the PTF method are compared with the results of a direct measurement conducted on the assembled system (see Fig. 4). The PTF method, which merely utilises information of the separate sub-systems such as structure, trim and cavity, shows high reliability and good predictability of the full-system behaviour.

Conclusions and outlook

The long-term goal is to adopt the enhanced PTF technique as a new, future approach for evaluation and target setting of automotive sound packages. In this respect one can fully exploit the main advantages of this technique, being an independent characterisation of the individual sub-systems and the full flexibility with respect to choice of the characterisation scheme.

References

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Reducing mechanical losses (friction) yields a significant contribution to reducing the fuel consumption. Therefore, VIRTUAL VEHICLE investigates all important sources of friction in the engine and the transmission both on the FRIDA friction test bench and by means of accurate simulation, in order to develop ideas for their reduction.

Along with lightweight construction and the shift of the thermodynamic load point in the engine (downsizing), friction reduction is a very effective way of reducing fuel consumption. On the race track, a friction-optimized drive train achieves a greater distance between pit stops for refueling and thus saves valuable time.

VIRTUAL VEHICLE investigates the drive train, which is a combination of engine and transmission, as a complete system. The combination of simulation and measurement is a very powerful tool which enables the most important sources of friction in the engine and transmission to be accurately identified. As a result, targeted optimizations can be prepared with this information.

**Friction measurements**

At VIRTUAL VEHICLE, there are several test benches available to measure the friction in the engine under realistic loadings. In particular, the friction test bench FRIDA (friction dynamometer, Fig. 1) offers very flexible possibilities for measuring the mechanical efficiency of engines and even complete drivetrains (e.g. for motorcycles under high loads).

Accurate and reproducible measurements also enable the exact determination of the advantages achieved by reducing friction when new coatings or low friction oils are used, which can consequently provide the technical basis for manufacturing decisions. The results can likewise be used to carry out benchmarks with existing solutions.
Classification of losses by simulation

While measurements are very useful, they cannot determine the causes or the main sources of friction in the engine or transmission.

For this purpose, very powerful and accurate simulation models have been developed at VIRTUAL VEHICLE, which enable a thorough investigation of the sources of friction in all relevant parts of the drivetrain.

Therefore, it is possible - for example after a frictional power measurement on the test bench - to accurately determine the losses in the individual groups, such as the pistons, journal bearings and valve train of a car engine. In this way, the total losses, as well as the valve train and gas exchange losses, are measured, and the losses in the journal bearings are accurately determined by simulation. The simulation method necessary for this was comprehensively validated and scientifically published in [1 and 2], among other places.

Using this combination of measurement and simulation, the distribution of the losses can be determined for a particular car engine for almost any operating point (speed and load). Fig. 4 shows a relevant example for a 4-cylinder car engine.

With these simulation models, it is also possible to investigate the lubrication conditions in these groups and the feasibility of the friction advantage that could be obtained by the use of low friction oils, for example. The necessary expertise in the field of modern low friction lubricants was obtained during the work on several projects. The relevant rheological lubrication data is available at VIRTUAL VEHICLE, which enables a meaningful evaluation of the lubrication.

Since the transmission is an important part of the drive train, it is also the object of friction investigations. In general, manual transmissions are considered to be very efficient. However, since this efficiency is only achieved at high loads, at low loads there is always a significant potential for friction reduction.

A simulation method has been developed at VIRTUAL VEHICLE that enables an assessment of the losses on the individual components to be carried out in conjunction with current efficiency measurements on transmissions.

In order to identify the important sources of friction in a transmission, a simulated friction loss distribution was carried out. Fig. 5 shows the results that were achieved for a manual
transmission. As an example, the transmissions investigated showed quite high conical roller bearing losses, which could be reduced by the use of alternative bearings.

**Detailed tribological investigations**

Even if friction occurs generally in all parts of the drive train, with some components, energy losses are less important than reliability in service, for example.

One example of such a component is the piston pin; its free-floating bearing causes hardly any frictional losses. Due to the increasing loadings caused by increasing power densities, it has to operate under increasingly extreme conditions (rising temperatures, lack of lubrication, etc.).

The problems with this apparently simple component increase significantly as a result. Since piston pin failure leads to serious engine damage, a very detailed and extensive simulation method was worked out at VIRTUAL VEHICLE to investigate this critical component.

A model was developed considering the thermo-elastic deformations of piston and pin, as well as the free-floating bearing, which was able to describe the slow rotary movement of the pin as well as its change of direction at certain operating points. The results were in good agreement with the measured data. Fig. 6 shows an example of the pressure distribution calculated with this model. This information can now be used for targeted optimizations of existing solutions.

In certain cases, available lower friction alternatives have other design disadvantages. It has long been known that roller bearings have less friction than journal bearings. Consequently, efforts have been made to replace the crank assembly bearings, which make up a significant part of the total losses, with roller bearings.

However, it is important to consider not only the higher manufacturing costs resulting from the use of roller bearings in this application, but also their unfavorable NVH (noise, vibration and harshness) properties. With the competence available at VIRTUAL VEHICLE regarding journal and roller bearings, it is also possible to make a comprehensive comparison of both solutions for the assessment of the friction and NVH properties.

**Conclusion**

Friction is a phenomenon that occurs everywhere. It is necessary to find a special solution for each specific problem, which typically means typically a suitable compromise with other requirements must be found.

At VIRTUAL VEHICLE, friction is considered as a property of the complete system. Therefore, models are available for all important assemblies, which also enable detailed investigations of other properties (NVH behavior, etc.). In particular, in terms of friction reduction, it is no longer possible to make significant savings by redesigning only a single individual component. Significant savings can only be obtained in conjunction with other measures, such as optimized thermo-management, reduction of the pumping power, ancillary units or the change to a low friction lubricant or use of coatings.

At VIRTUAL VEHICLE, the ability to consider the complete system as a combination of
measurements and detailed simulation enables realistic investigations of the potential for friction reduction, and the identified friction advantages can then be achieved in practice.

References:

Test rig to determine engine friction losses

- Reliable measurements for gasoline and Diesel engines
- For series engines and prototypes
- Concurrent determination of losses in sub-systems
- Partial- and full load engine tests
- High flexibility for various applications

The Friction Dynamometer FRIDA has been developed at VIRTUAL VEHICLE. This test bench can measure not only the magnitude of the total friction losses in the engine, but can also determine the specific contributions of the individual components (i.e. the piston assembly, crank drive friction bearings and valve train). In contrast to conventional strip-down methods, these measurements are carried out concurrently for all subsystems under the same realistic operating conditions.

The newly established test bench is well-suited for a variety of applications - from friction loss determination in driving cycles to the assessment of coatings, low-viscosity engine oils or other constructive measures.

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AN EXPERIMENTAL METHOD FOR THE NVH CHARACTERIZATION OF ELECTRIC MOTORS

Automotive industry is asking for new methodologies to characterize the acoustic emissions of electric motors, since their integration in EVs and Plug-in-Hybrid vehicles is growing. At VIRTUAL VEHICLE we are developing an experimental methodology based on cylindrical Nearfield Acoustical Holography. This allows the evaluation of sound intensity, as well as pressure level and particle velocity. It is suitable for any type of electric motor without knowing either the internal geometry or the material properties.

Need for new NVH methodologies suitable for electric vehicles

Automotive industry is increasingly driven by the need to offer fuel-efficient and eco-friendly mobility. This is mainly achievable by lightweight design, downsizing internal combustion engines, and powertrain electrification and hybridization. Moreover, customers are asking for comfortable and innovative vehicles.

In order to accomplish customer expectations, new NVH approaches are required. They have to deal with new materials, components and powering strategies. In this framework, the prediction and characterization of the noise of electric motors plays a crucial role.

State-of-the-art for electric motor NVH simulation

There are three main approaches to predict or characterize the vibro-acoustic behavior of an electric motor, i.e. analytical, numerical and experimental.

Analytical approaches are usually fast and simple to apply, but their high accuracy is limited to very simple geometries.

Numerical methods (finite and boundary elements) can include fine geometry details, but have as drawback a less flexible workflow and long computational time, especially if high frequencies are included. Moreover, the full knowledge of the material properties is needed. In practice, this turns out to be extremely difficult for coils and lamination pack structures that are typical for some motor types.

Measurements are then the most reliable way to characterize the motor as an airborne sound source. At Area NVH & Friction we are developing an experimental method to characterize the airborne noise emission of electric motors, which are typically almost cylinder-shaped. This characterization method is based on acoustical holography in cylindrical coordinates, i.e. implying the measurement of the sound field in discrete positions on a cylindrical surface around the electric motor [1].

Proposed methodology

Cylindrical Nearfield Acoustical Holography (NAH) allows an accurate localization and characterization of a source through the back-propagation of a hologram, being thus extremely well suited for cylindrical sources like electric motors.

Cylindrical NAH consists in the following four steps:

1. measurement of the pressure on a grid of points on the hologram surface (i.e. microphone positions)
2. computation of its spectrum through a spatial transform
3. propagation of the spectrum and reconstruction of the velocity distribution on the source surface
4. back-transformation to the real space

Fig. 1: Electric motor surface (green points) and microphone positions (blue stars)
We created a numerical test case to investigate practical aspects of cylindrical holography such as hologram size and possible sources of error. Such simulations allow for designing an effective experimental setup.

Fig. 1 shows the geometry of the test case; the green points represent an acoustic source (motor) while the blue stars are the microphone positions.

NAH is based on an inverse problem, which is sensitive to small input variations (e.g. measurement noise). The robustness of the method is enhanced by filtering the noise components (i.e. regularization).

Fig. 2 shows this regularization effect at a single frequency step along the circumference of the motor and emphasizes the importance of this step for NAH.

Practical aspects of cylindrical holography

Several scenarios have been examined in order to investigate practical aspects of cylindrical holography such as microphone positioning error, background noise, hologram distance, spatial sampling, measurement aperture. Fig. 3 and 4 show the spatially averaged square error ($\varepsilon$) for different hologram distances.
lengths and microphone positioning errors, respectively. It can be observed in Fig. 3 that for a microphone array of 1.5 times the motor length, the maximum error is within the 3 dB range. Furthermore, the same error band includes the effects of a microphone positioning error of up to 8 mm (Fig. 4).

Conclusions and future work

Cylindrical NAH is an efficient method for the characterization of the acoustical emissions of electric traction motors for next generation green vehicle applications.

Numerical simulations at VIRTUAL VEHICLE have already shown that cylindrical NAH - together with an appropriate regularization scheme - gives accurate results for the reconstruction of the surface velocity of an acoustic source like an electric motor.

Measurement noise can be limited by choosing anechoic test environments. The typical magnitude of this noise does not compromise the results.

Cylindrical holography allows for accurate acoustic characterization also in the presence of sources located on the end caps of the electric motor, such as a cooling fan and bearings.

The frequency range is limited by the number of microphones used. Future work will further investigate the topic in order to understand how many microphones can be excluded without compromising the results.

Free-field measurements on a real electric motor will be performed in an anechoic chamber in order to verify and validate the proposed methodology.

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FREE-FIELD MEASUREMENTS ON A REAL ELECTRIC MOTOR WILL BE PERFORMED IN AN ANECOIC CHAMBER IN ORDER TO VERIFY AND VALIDATE THE PROPOSED METHODOLOGY.
VVM: What are the main current trends in automotive R&D concerning NVH?

AYOUBI: The first essential trend is the increased expectations of the customers with regard to NVH comforts. In this respect, not only the noise level is crucial, but also the NVH coherence between wind-/tire-/powertrain-N VH in the vehicle is becoming increasingly important.

The second defining trend is of course lightweight construction and emission reduction with direct interaction with NVH. The employment of new materials such as carbon fiber reinforced plastics and aluminum, the trend towards downsizing and down-speeding, the electrification and hybridization entail many challenges for NVH engineers.

VVM: Where do you see the most important technical challenges of NVH-related vehicle development?

AYOUBI: The largest challenge for the NVH development in the vehicle is the expansion of the physical understanding of the relevant NVH causal loops. For me, a causal loop is only fully developed when it is also depicted in the virtual world. Only then it becomes possible to develop the NVH property through objective goals in a directed manner, from the design to the integration and validation.

Some NVH phenomena were understood very well and also depicted operatively in the virtual world. This is the case with powertrain NVH. However, I have also observed that the depiction of other NVH phenomena in the medium and high-frequency areas can be significantly extended. This primarily affects phenomena for tire and wind NVH.

The goal has to be to analyze, design and validate as much of the NVH world in the vehicle as possible via virtual prototyping because virtual prototyping has become an essential developmental tool in the development process.

VVM: In which phases of the BMW vehicle development process is NVH integration currently of particular importance?

AYOUBI: Generally speaking, in the past NVH development focused more on the integration phase. In this phase, the analysis, problem-solving, and optimization were always handled using HW-prototypes.
Since then, we have made a significant leap towards a more balanced NVH development throughout the product development process. To this end, basic NVH elements are designed iteratively at a very early stage via simulation and simulators (global and dynamic stiffnesses, aerodynamic shapes, integration of transmission and chassis,...).

VVM: And how do you think this will change in the future?

AYOUBI: The trend towards an early NVH integration via virtual prototyping and NVH simulators will be expanded. The product development process is essentially based on two phases: an architecture phase and a derivate development phase.

The goal of the architecture phase is to design the NVH genes for a broad platform in a target-oriented fashion. I am talking about the NVH backbone of a platform. Clearly, errors in this respect have significant consequences on later derivatives. The second challenge of this phase lies in the lack of hardware prototypes. This is where NVH simulation in the sense of NVH virtual prototyping plays a key role. This is the reason why I see the expansion of the understanding of the physical NVH causal loop as the primary challenge for NVH development. Only this can enable a reliable NVH virtual prototyping.

In the second derivate development phase, the NVH character should be applied based on a well-designed platform for each vehicle derivate, in order to guarantee a segment-specific positioning.

Virtual prototyping has become an essential developmental tool in the development process.

VVM: How do you see the development of EU legislation concerning noise emission, and what are the consequences for BMW?

AYOUBI: The advanced draft proposals for exterior noise call for new boundary values and new test cycles.

With the previous test specifications, the powertrain was the dominant source of exterior noise. With the new test cycle, the tire will now become the dominant emitting source. Consequently, the automotive and tire industry has to develop new technologies in order to meet the challenging tire goals such as rolling friction, driving dynamic, breaking distance, or NVH.

VVM: Will it be possible to replace experimental NVH investigations in the vehicle development process completely with simulation within the next ten years?

AYOUBI: Simulation, driving test, and test bench trials are development tools that focus on different applications. The product development process passes through different phases, in which specific questions are prioritized. To this end, the phase-adequate deployment of one or more tools is necessary. In the early phase, in which there is no hardware, simulation plays a central role. In the later phase, in which the refinement takes place, the experimental trial is the faster way.

VVM: What is the BMW strategy for handling the trade-off between lightweight design and acoustic comfort?

AYOUBI: Many small steps will be required to resolve the conflict in objectives between lightweight approaches and NVH and to produce an optimum solution.

To this end, one essential step is a sound NVH backbone in the form of static and dynamic stiffness. It is also becoming increasingly important to prevent noise emission at its source, before the energy goes downstream into the body. In the body, new lightweight materials with good dampening characteristics are necessary.

VVM: Where do you see potential for improvement in conventional drivetrain NVH?

The emotionalizing effect of sound only transpires through the context and interplay of all senses - haptic, optic and acoustic- in the vehicle.
Source: BMW
AYOUBI: High supercharging, downsizing, downspeeding are dominant trends in the powertrain development with NVH conflict. In this context, it is imperative to ensure further NVH isolation close to the source and within the internal engine.

VVM: Which R&D achievements in your area of responsibility are you most proud of?

AYOUBI: I think right away about the i8. With the i8, we have introduced a technology carrier with many innovations, including the carbon-fiber body, a highly supercharged 3-cylinder across the back axle, a directly connected chassis and a life-drive module, to name but a few. All these topics were a huge challenge for powertrain-, tire- and wind NVH.

We are quite proud of the result. Driving the i8 brings an intense emotional driving pleasure.

VVM: What is characteristic and relevant for a high-quality brand sound at BMW?

AYOUBI: Sound design at BMW is authentic. Sound design is not a question of the powertrain alone. The perception of the engine torque disappears after seconds of accelerating. It is much more important that we fulfil customer expectations regarding exterior and interior design and the feeling of space within the vehicle. The emotionalizing effect of sound only transpires through the context and interplay of all senses - haptic, optic and acoustic-in the vehicle.

VVM: What are the demands for NVH engineers at BMW? What attributes and values should they represent?

AYOUBI: We place value on an exceptional education, a marked proactive behavior, the ability to take a systemic perspective, and a tangible passion for the product and the topic.

**High supercharging, downsizing, down-speeding are dominant trends in the powertrain development with NVH conflict.**

VVM: What are your expectations in a research partner?

AYOUBI: A cooperation partner should have a sound theoretical competence and at the same time a strong emphasis on practical applications and an economical implementation. A project should not take too long to deliver results. In executing projects, our partner should have a similar work culture to that of BMW. Passion, perfection and the never-ending love for the product. A partner that needs to be led by the hand does not exhibit the desired proactive behavior.

VVM: What is your experience in cooperating with VIRTUAL VEHICLE?

AYOUBI: VIRTUAL VEHICLE has an impressive network of competent and highly motivated experts who pursue an interdisciplinary approach. I like that.

Dr. Mihiar Ayoubi has been interviewed by Dr. Anton Fuchs.

Graduate degree and doctorate in Control Systems Engineering from the Technical University of Darmstadt. Joined BMW in 1997. Held various positions in the series development of mechatronic systems, such as electronic steering systems, breaking control systems, all-wheel-drive systems, manual transmission, powertrain and vehicle assistance systems. Since 2011, VP of acoustics and vibrations in the full vehicle.

Dr. Ayoubi is one of the distinguished Keynote Speakers at the ISNVH 2014 Congress in Graz: „Challenges of virtual prototyping for premium NVH comfort - an overview of current BMW engineering practices“.

More information: [www.isnvh.com](http://www.isnvh.com)
Since 1960 the commercial diesel engine’s fuel consumption was reduced by one third. Due to decades of research a 40-tonne truck nowadays only needs 32 liters per 100 km. At test drives, an average consumption of even 20 liters per 100 km was achieved. At their best point of operation, such engines feature an efficiency of almost 50%.

Franz M. Reich has asked Jürgen Ritter, Andreas Sommermann (both MAN Truck & Bus AG) and Christoph Priestner (AVL List GmbH) on future trends in engine development for heavy duty vehicles.

VVM: Which development potential do you perceive in the optimization of tribology and powertrain or the automatic transmission in combination with ADAS and navigation data?

RITTER: The tribological optimization of commercial vehicle engines comprises the following fields: optimization of the friction partners, the lubricants, demand regulated auxiliaries, fundamental redesign and lubricant conditioning. For long range traffic we expect up to 6% reduction of fuel consumption in the long range.

SOMMERMANN: Every type of friction reduction affects the fuels consumption and heat transfer and even the emission values positively, whereby the emission values refer to the engine power. The power train of the future will assist the driver in the best possible way. In this domain, we perceive the greatest fuel saving potentials. Of course, by considering the topographic data, further 3% fuel can be saved.

VVM: Is it the trend of development to keep on heightening the BMEP and the peak pressure? How is the tradeoff between larger friction and the combustion thermodynamics?

RITTER: The optimal peak pressure determination in the tradeoff friction versus thermodynamics is an extremely crucial development topic, which we want to solve by means of simulation.

SOMMERMANN: This question affects almost all disciplines of engine development. Currently, we observe the trend of increasing the mean effective pressure of the engines, but not necessarily linked to a strong increase of the peak pressure. An engine trimmed to extreme peak pressure values has the disadvantage of increased mean friction pressures at partial load.

PRIESTNER: The current trend of downspeeding shifts the operating point to lower rotational speeds and higher average cylinder pressures (BMEP). Once the average friction pressure loss (FMEP) is known, the reduction of fuel consumption can be read out of the fuel consumption performance map. For a safe
operation at these low rotational speeds and high average cylinder pressures, the crank shaft bearings, the oil pump, the water pump and so on must be adapted appropriately. These necessary measures lead to a higher FMEP, which curtails the potential of fuel consumption reduction.

Never the less some 1-2% are estimated for the potential of fuel consumption reduction in the relevant load range of long distance traffic applications.

VVM: Which potentials are expected from the combination of “auxiliaries-on-demand” and “predictive driving”?

SOMMERMANN: This is the subject of very intensive research projects. The effects on the complete system are very comprehensive, because each auxiliary gadget must first be considered on its own, and then in the ensemble of the complete power train. The potential of GPS enhanced auxiliaries-on-demand strongly depends on the individual case. The more mountainous the course is, the better the effect of the prediction. It is difficult to state a specific value therefore.

VVM: Can the friction loss measurement in the fired engine be replaced by friction loss measurements with motoring?

SOMMERMANN: The methodology of tribological loss differentiation via friction loss measurement on the complete engine with motoring is a third alternative next to friction loss measurement on the fired engine and friction loss measurement on a partially stripped down engine with motoring. The methodology developed at VIRTUAL VEHICLE ensures the following technical features: a high quality of reproducibility and a high measurement accuracy. The determination of friction losses of valve drive, piston assembly and crankshaft slide bearing occurs at the same time under identical operation conditions. Within the K2...
research project with MAN and AVL, a D26 MAN engine is analyzed and evaluated with the new methodology. In any case, this methodology possesses a high potential to boost the efficiency of engine development.

PRIESTNER: The added value of the tribological loss differentiation via motoring originates in the efficient friction measurement on component level under realistic conditions of the cylinder pressure.

While motoring, the heat transfer of the combustion into the engine structure is missing. Consequently the bearing clearances and viscosity, which influence the friction, are different from those at fired engine operation. Thus motoring represents an approximation of the engine's real operation conditions.

The strong point of the motoring methodology in comparison to the friction loss measurement in fired operation lies in the efficient comparison of components relative to each other in the operational map of load, rotational speed and temperature. For example, the effect of the piston rings tension can be analyzed in this way. As Verification for the identified potentials, the fired friction loss measurement with real operating conditions is employed.

VVM: Which potentials do you see in the usage of new materials for the engine block – currently about one metric ton heavy – for the reduction of the fuel consumption?

RITTER: For long distance traffic we only perceive a small potential. A weight reduction of 100 kg reduces the fuel consumption by 0.2%. In traffic related to distribution and in city busses we see a larger potential.

SOMMERMANN: I agree with the statement of Mr. Ritter. Additionally, we must bear in mind that the measures mentioned above reduces the influence of weight.

VVM: What does MAN – or what do you – expect from the cooperation with VIRTUAL VEHICLE and AVL in the current research project? Which experiences did MAN – or did you – have? Why do you work together with VIRTUAL VEHICLE?

SOMMERMANN: The cooperation of MAN, VIRTUAL VEHICLE and AVL in research projects provides all partners with the opportunity to expand their scope of knowledge. The topic of friction can be accessed from different points of view. All partners can derive new calculation and simulation methods from this intensive research activity, which will help design engine with less friction. The benefit for our customer is a more efficient engine with the best possible fuel consumption.

Wireless measurement - easy and exact:

Wireless measurement
- Torque measurement
- Integration of the measurement system into the drive shaft
- Data transfer via Bluetooth
- Inductive power supply

Easy integration
- No demounting of components of engine compartment
- Contact free measurement of fuel consumption of auxiliaries
- Simple measurement set-up

Numerous application possibilities
- Air flow through engine compartment
- Air flow through cooling package
- No influence of pressure tubes – only one wire necessary

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A SUCCESSFUL PARTNERSHIP

The Marcus Wallenberg Laboratory for Sound and Vibration Research (MWL) at the Royal Institute of Technology (KTH) in Stockholm, Sweden has supported K2 projects led by VIRTUAL VEHICLE: Together with people from VIRTUAL VEHICLE acoustic measurements have been conducted on the acoustic flow test rigs available at KTH.

The Royal Institute of Technology (KTH), Stockholm, Sweden, is the largest technical university in Sweden and is divided into nine schools. The Marcus Wallenberg Laboratory for Sound and Vibration Research (MWL) is a division of the Department of Vehicle and Aeronautical Engineering (www.ave.kth.se) and belongs to the School of Engineering Science. MWL as a KTH centre for Technical Acoustics was founded in 1977 and is today one of the larger university centres for Technical Acoustics in Europe with four full time professors and a total staff of around 30.

MWL is also offering an international MSc program in Sound and Vibration as part of the Engineering Mechanics programs at KTH. The research focuses on transportation related applications and can be split into three main areas:

- Flow Acoustics
- Material and Structural Acoustics
- Vibro-Acoustics

The research approach is a combination of theoretical work leading to numerical models and advanced experimental investigations. This approach is supported by the excellent laboratory facilities at MWL that include acoustic test rooms (anechoic, reverberant, and semi-anechoic) and special flow test rigs that can be connected to these rooms.

KTH as a Scientific Partner of VIRTUAL VEHICLE

The scientific cooperation with KTH started during the time of the Acoustic Competence Centre (ACC). The first project done with KTH as scientific partner and with AVL List GmbH as industry partner was on “Linear Acoustics of Mufflers in the Higher Frequency Range”. The aim of that project was to accurately predict the acoustic properties of a complex exhaust muffler under the presence of mean flow. The different components of a muffler—perforates, absorptive materials and resonators were acoustically modeled using 1D linear acoustic two-ports. These different components were then used to build up models of different muffler configurations in order to study how these components acoustically interact. Acoustic two-port experiments of the prototypes of the mufflers were then performed on the acoustic flow test rig at KTH in order to validate the models. From this project, two Master theses were completed under the supervision of KTH: “Investigation of the Acoustic Performance of Dissipative Mufflers: Influence of Different Absorbing Materials and Packing Densities” by Yasser Elnemr and “Linear Acoustic Modeling and Testing of Exhaust Mufflers” by Sathish Kumar.

From the aforementioned project, the work by the graduate student Ying Guo under the supervision of KTH lead to a Licentiate’s degree, which is a pre-doctoral degree awarded in Sweden. The thesis was titled “Investigation of perforated mufflers and plates”, which was partly done under the European Commission project SIMVIA 2 (partially hosted by VIRTUAL VEHICLE). Together with Prof. Mats Åbom and Dr. Sabry Allam VIRTUAL VEHICLE published two papers on “Micro-Perforated Plates for Vehicle Application” (presented on Inter-Noise 2008) and “Acoustical Study of Micro-Perforated Plates for Vehicle Applications” (presented in the 2009 SAE Noise and Vibration Conference).

In a follow-up project on “Enhanced performance of intake/exhaust system orifice noise simulation”, the components of the intake and exhaust line-turbochargers, intercoolers and after treatment devices were modeled using non-linear acoustic simulation (1D gas dynamics). For the verification of the intercooler and after treatment device models, acoustic two-port measurements have been conducted on the flow acoustic test rig at KTH. For the verification of the turbocharger models, acoustic two-port measurements were done on KTH’s then newly developed acoustic turbocharger test rig (KTH-CCGEX). Under the supervision of the KTH, a Master thesis by Rafael Velloso titled “An Investigation into the Passive Acoustic Effect of an Automotive Turbocharger Compressor” and a Licentiate thesis by Yasser Elnemr titled “Acoustic Modeling and Testing of Exhaust and Intake System Components” were completed.

MWL is a steady and valuable scientific partner for VIRTUAL VEHICLE. Currently, KTH is scientific partner in a K2 research project in Area NVH & Friction on turbocharger passive and active acoustics. Prof. Abom also supports the 8th ISNVH Congress, among others as a member of the Scientific Program Committee. We are looking forward for further fruitful cooperation.

ABOUT THE AUTHOR

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In automotive industry vehicles are assembled from complex components, many of them being specialised sub-assemblies themselves, coming from different disciplines and suppliers and following separate design and development processes. Moreover, different subsystems are frequently being designed and developed in parallel by different specialised teams within the same automotive industry, in order to further reduce the time-to-market. Early stage optimisation of the assembly is consequently hampered by the fact that detailed information of some component systems is missing.

On top of this, different components may be combined in different ways depending on the product requirements. Examples are for instance different powertrain variants which share the same crank-case, single engines which may be equipped with a range of hybrid transmission architectures, different cars which mount the same engine. Again, system optimisation is difficult as an acceptable trade-off must be found which suits many system configurations.

The challenge consists in the formulation of design and optimisation strategies which can guarantee the fulfilment of assembly level performance targets despite the uncertainties or variability with regard to some of the component systems.

Solution principle

The solution proposed in this article consists in defining equivalent sub-systems describing generic component systems which exact details are insufficiently known to allow detailed modeling. If possible these equivalent sub-systems shall be defined in such a way as to keep the essential wave interaction mechanisms of the assembly intact. The boundary conditions which are hereby installed shall describe the unknown systems in an average sense, meaning that they should be representative for all relevant structural configurations.

The formulation of such equivalent sub-systems is based on the fact that the vibratory field of any component system can be subdivided into a direct and a reverberant field. The reverberant field depends on the exact details of the component and is specific for a given structure. The direct field, on the other hand, only depends on few generic structural parameters such as the average wall thickness, the shape of the structural interface and the material data, and is characteristic for all structures which share these parameters. This direct field can be obtained by eliminating the reflections coming from the “uncertain” boundaries.

Illustrative example

Here a simple example is given to clarify this concept. Consider a component system consisting of a flat 1 mm thick steel plate with a well-defined shape (see Fig. 1). The mobility curve pertaining to the contact point of this plate was calculated and is shown in Fig. 2 (red line, finite system). The numerous peaks and dips are associated with the vibration modes of this particular plate, any adaptation of its shape will also change its modal behaviour.

Now suppose that the plate features a well defined geometry around the contact point (“known area” in Fig. 1) whereas the rest of the plate may take any shape (“uncertain area” in Fig. 1), can we still describe the general features of its mobility curve? This can be achieved by removing the reflections from the “uncertain” boundaries. For the plate under consideration the fastest waves take
1.75 ms to travel from the contact point until the boundary of the “uncertain” system, any reflection coming back to the contact point within 3.5 ms will consequently only contain information about the known area and will characterise this plate whatever the shape of the uncertain boundaries. The blue curve in Fig. 2 was obtained by truncating the impulse response of the plate at 3.5 ms and back-transforming it in the frequency domain. This curve indeed describes the mean behaviour of the system whereas the modal information due to reflections of the uncertain boundaries has been removed.

**Automotive application**

Clearly, the reflections from the uncertain boundaries can also be removed by damping the system in such a way that waves traveling towards uncertain boundaries are progressively dissipated while they penetrate, without causing reflection.

In Area NVH & Friction of VIRTUAL VEHICLE a methodology is being developed which allows to achieve such specific absorption features simply by using conventional dashpot dampers. The procedure under development provides indications with regard to the precise amount of damping of the dashpots and their positioning, yielding a stable and efficient calculation model which can be implemented in any commercially available FEM code.

An example is given in Fig. 3. This figure shows the transfer mobility between two positions on an oil sump connection flange. These mobilities characterise the oil sump as it is “seen” from the rest of the engine structure. During optimization this oil sump is preferably substituted by a generic structure as the engine must yield optimal NVH performance with different types of oil sumps. The smooth curve represents the mobility of the equivalent structure obtained with the new procedure, whereas the spiky curve represents the mobility of one of the real life sumps. The peaks and dips are due to the vibration modes which characterise this particular component. The equivalent oil sump indeed displays the same average trend without showing case-specific modal behaviour. One can indeed imagine that by averaging over different oil sumps the eigenfrequencies tend to cancel revealing the smooth generic oil sump curve as displayed in the figure.

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EUGENE NIJMAN is Scientific Head of Area NVH & Friction at VIRTUAL VEHICLE.

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**Fig. 2: Driving point mobilities of the plate sub-system**

**Fig. 3: Transfer mobility between two points of an oil sump connection flange - actual and substituting equivalent structure.**
Improved Real-time Simulation

VIBRATION COMFORT BASED ON A PARALLEL-HYBRID EXAMPLE: REAL-TIME DRIVE TRAIN MODELS

Future legislation will demand that manufacturers make further significant reductions in fuel consumption and vehicle emissions. At the same time, it is also necessary to maintain the present high level of comfort in modern vehicles. Using extended real-time simulation models of the drive train for vibration phenomena up to about 100 Hz, it is possible to optimize these competing requirements for future vehicles in the early development phase by means of hardware-in-the-loop test equipment. To this end, VIRTUAL VEHICLE has developed new methods for reducing low-frequency drive train vibrations taking a parallel hybrid design as an example.

There are many guidelines in the literature for the simulation of Noise-Vibration-Harshness (NVH)-phenomena in the drive train. In particular, these guidelines describe analysis using detailed off-line simulation models (which do not require that calculations are done in real time) with commercially available multi-body simulation (MBS) and finite element (FE) software. They also provide detailed information on the modeling and parameterizing of non-linear components in the drive train and their effects on the quality of the results.

In contrast, real-time simulation models of the drive train, which are necessary for HIL applications or drive simulators, are characterized by the very small number of degrees of freedom necessary for real-time. With these real-time models, low-frequency vibrations (<20 Hz) can be reproduced with sufficient accuracy in the simulation. Simplified models are often used for non-linear components, such as for modelling a dual mass flywheel by a spring-damper element. The simulation of higher frequency drive train vibrations of up to about 100 Hz, however, shows significant weaknesses in the quality of the prediction because of the simplified model sets and the reduced degrees of freedom.

Improved real-time simulation models for low-frequency NVH phenomena in the drive train

The real-time simulation of low-frequency NVH-phenomena (up to about 100 Hz) in the drive train requires improved modelling and parameterizing for non-linear components. The models must have the necessary calculation efficiency (real-time capability) and be able to reproduce the relevant non-linear behavior. The example below describes the improvements in the model for the chosen sub-systems in the drive train, which have met the desired objectives.

Model automatic gearboxes

The partial systems that are particularly relevant for fuel consumption and vibration comfort are the hydrodynamic torque converter, the lock-up clutch and the mechanical torsion damper. For the torque converter, results have shown that a characteristic map-based approach for modeling vibration phenomena up to 100 Hz offers a good compromise regarding calculation efficiency and results quality. The reaction torques can be calculated based on the converter characteristic and the speed ratio between pump and turbine wheel. Due to

Fig. 1: Modular drive train model and model vehicle set up with 16 degrees of freedom.
fuel consumption requirements, it is necessary to lock-up the converter shortly after the starting process using a clutch. In order to ensure that the vibration comfort is acceptable at all times during the locked up state, mechanical torsion dampers are fitted in series with the clutch (conventional arrangement), with the turbine wheel (turbine torsion damper) or combined (2-damper converter).

The model for the automatic gearbox developed at VIRTUAL VEHICLE can show all relevant operating conditions by means of sub-models:

- Engaged clutch, engine drive
- Open or slipping clutch, engine drive
- Engaged clutch, propulsion drive
- Open or slipping clutch and converter operation, propulsion drive

The active operating condition is defined by the speed ratio and the gearbox input and output torque.

To calculate fuel consumption, a load-dependent and speed-dependent loss characteristic field is included for the actual automatic gearbox (planetary gears). The losses in the converter are considered directly by means of the speed ratio between turbine and pump. Auxiliary units (e.g. hydraulic pumps) are considered in the loss characteristic.

Reduction of shuffle vibrations on an HEV (Hybrid Electric Vehicle)

The low-frequency NVH shuffle phenomena is characterized as follows:

- Initial torsional natural mode of the vehicle and drive train
- Vibration nodes in the side shafts (engine vibrates against the vehicle)
- Excitation by sudden torque changes (accelerator position changes)

VIRTUAL VEHICLE investigated the possibility of reducing the shuffle vibrations of an HEV in a concrete application. The E-motor was controlled by means of the principle of disturbance magnitude compensation, in which the input signal can be measured as the disturbance variable for which the controller compensates. A simplified system of 4 masses was used for the control design. The tire model which converts the wheel torque (rotary movement) allowing for the wheel slip into a translational force (linear movement) of the vehicle mass also uses these means to consider a speed-dependent damping which affects the bucking frequency.

The model of the E-motor (permanently excited synchronous machine) is reproduced with the appropriate field-orienting control with a space indicator display in the model. The DC/AC converter required between battery and E-motor is modelled in a simplified way as a function of the pulse width and input voltage. A super cap serves as an energy storage device, since the current battery does not have the necessary short-time power density. With an E-motor rating of 15 kW, vehicle shuffle vibrations on a middle range car can be sufficiently compensated for (Fig. 2).

Summary

Using the improved drive train model set up at VIRTUAL VEHICLE, which is capable of working in real time, vibration phenomena up to 100 Hz can be investigated in detail, simultaneously with fuel consumption analysis. The modular model set up makes it possible to analyze a wide range of different conventional drive train configurations. An additional module for integrating electrical components enables the optimization of vibration phenomena in HEVs.

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THE TEST BENCHES
OF AREA NVH & FRICTION

VIRTUAL VEHICLE operates comprehensive test facilities designed to investigate the acoustic properties of vehicle components such as the engine and drivetrain. These test facilities play an important role in solving R&D challenges in NVH and friction fields.

History of the Test Centre

Construction of the test benches began fifteen years ago, shortly after the founding of the Acoustic Competence Centre (ACC). Since spring 2000, tests have been carried out as part of customer and research projects on two acoustics test benches, one for the engine and one for the drive train, as well as the modal analysis test bench. In June 2008, ACC including its test benches has been integrated into VIRTUAL VEHICLE Research Center.

Due to today’s ever tougher challenges, and also in view of the nature of the tests themselves, the test benches have been upgraded on several occasions to meet the latest technical standards:

- 2005: Upgrade of the test bench controller on the engine and drive train test benches to AVL Puma Open
- 2007: Use of an automatic gear shift unit to carry out automated test runs on the drive train test bench
- 2009: Acquisition of a climate chamber (-20 °C to +60 °C) for the drive train test bench
- 2012: Upgrade of the engine and drive train test benches to AVL Puma Open 2011 and adaptation of the power electronics (frequency converter and controller) on the drive train test bench
- 2011: Certification to ISO 9001 for the first time. Subsequent certifications have been carried out at regular intervals (most recently in May 2014).

Engine acoustics test bench

This test bench is a fully anechoic acoustic chamber with a lower frequency limit of 100 Hz. It can operate internal combustion engines up to a maximum power of 440 kW and can be used to test both high-speed Otto engines for passenger cars (maximum speed: 7500 rpm) and high-torque truck engines (in conjunction with intermediate gearbox of up to 3600 Nm) (Fig. 1).

It is important to mention that this test bench is also equipped to enable testing for research projects designed to reduce emissions with a view to future exhaust standards. A comprehensive research project on this topic is currently ongoing. Thus, in combination with the acoustic equipment, outstanding framework conditions are available, especially for the analysis of linked tasks (e.g. the "effects of reduced emissions on the engine acoustics" or "acoustic optimization taking emissions into account").

Certification

In 2004, the entire testing equipment was certified to ISO 9001 for the first time. Subsequent certifications have been carried out at regular intervals (most recently in May 2014).
Drivetrain acoustics test bench

This all-wheel-drive train test bench is a semi anechoic chamber with a reverberative floor and a lower frequency limit of 100 Hz (Fig. 2). Four dynos with 218 kW each are available on the test bench for control functions.

Not only front and rear-wheel drives, but also all-wheel drives up to a maximum power of 400 kW can be tested; the autonomous control of the four dynos also permits the simulation of cornering (such as for turning circle abrasion). In addition to the complete drivetrain set-up with an internal combustion engine, operation with an electric motor (in addition to the four dynos) is possible.

This variant is often in use, particularly for transmission tests. In addition to the acoustic and vibration tests mainly carried out in the past, as well as function tests (e.g. endurance run, differential stability test), the range of applications was extended as part of a research project on the efficiency of transmission systems. Extensive know-how has thus been built up in the Area NVH & Friction in the fields of measurement technology and calculations/simulations (hypoid and beveloid gears).

A climate chamber has also been in use since July 2009, which allows the transmissions to be cooled down to -20 °C, thereby enabling the measurement of efficiency and vibration at low temperatures.

All test runs can be carried out fully automatically.

Modal analysis test bench

The modal analysis test bench can be used to test the vibration of objects up to a mass of 4 tons on a decoupled test plate with dimensions of 3.5 m x 6 m (Fig. 3). The relevant vehicle parts (e.g. trimmed body, bodywork, drive train) or parts of rail vehicles (e.g. wheels, bogie) are excited by a shaker (up to 1000 N) or an impact hammer. Accelerometers and a laser scanning vibrometer are used to measure the vibrations. The absorption and noise reduction values can be measured at the Test Centre in a small echo chamber (comparable to an alpha cabin) or at the nearby Institute of Building Construction of Graz University of Technology, either in its sound transmission test bench or its echo chamber.

An acoustic holography system is available for special tests in the field of noise emissions.

Several mobile and stationary measurement systems are used for the acoustic and vibration tests.

Friction loss test bench for series engines (FRIDA)

To determine the friction losses in engines under realistic operating conditions, an innovative friction loss test bench (Friction Dynamometer: FRIDA) was developed at VIRTUAL VEHICLE.

This test bench can measure not only the magnitude of the total friction losses in the engine, but can also determine the specific contributions of the individual components (i.e. the piston assembly, crank drive friction bearings and valve train). In contrast to conventional strip-down methods, these measurements are carried out concurrently for all subsystems under the same realistic operating conditions (both full load and any required partial loads are possible), which makes this approach clearly superior to the usual strip-down procedure.

The newly established test bench delivers results on aspects relevant to research projects and services.

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Emerging NVH challenges

Lightweight design as well as electrification and downsizing of the powertrain are common strategies in automotive industry to reduce exhaust emissions and increase fuel-efficiency while keeping at least the same vehicle performance. Unfortunately, adopting these strategies typically worsens NVH parameters compared to vehicles employing conventional car body and powertrain approaches.

Due to tight legal regulations, well-trained researchers are required to further develop low-emission vehicles. For NVH-related topics in vehicle development, experts are needed that are able to handle competing demands of electrified or lightweight vehicles and NVH requirements.

VIRTUAL VEHICLE has taken over a very active role in establishing a research and training network funded by European Commission within the framework of Marie Curie Actions. Investigations on the interaction between lightweight design, alternative propulsion approaches and NVH are a relevant part in all three Marie Curie projects at VIRTUAL VEHICLE, where Area NVH & Friction is involved.

Lightweight design vs. NVH

In order to reduce weight, alternative materials for vehicle body and interior design have been increasingly applied in automotive industry over the recent years. Besides well-established materials such as aluminium, new approaches like lightweight sandwich panels are more and more adopted from aerospace industry into automotive applications. These structures are typically laminates consisting of a honeycomb core and fibre reinforced plastic face sheets. The way the NVH properties of these anisotropic materials can be characterised experimentally or numerically differs substantially from those commonly applied: The lightweight panels exhibit for example only weak sound insulation properties at low frequencies, since air-borne transmission is mainly driven by the mass of the structural partition.

Alternative propulsion vs. NVH

Recently, electric propulsion has been gaining importance in the automotive sector motivated mainly by the need to reduce CO₂ emissions and the dependency on fossil fuels. Due to the several favourable features of an electric motor, such as high efficiency, nearly zero emissions and high torque available from zero revolution, its integration in a vehicle powertrain is favoured. Nevertheless, its distinctive acoustic appearance is typically being accepted as annoying by the customers, even though the overall noise radiated is usually lower compared to the internal combustion counterpart.

The lower noise emission of an electric motor also implies that secondary noise sources become more dominant contributors to the overall noise of a vehicle.
Research Fellowship Programme at VIRTUAL VEHICLE

At present, Area NVH & Friction is very active in three Marie Curie projects:

In 2011, VIRTUAL VEHICLE proposed a unique training programme designed to educate future automotive scientists in the respective multidisciplinary fields. In the four years project GRESIMO – “Best Training for Green and Silent Mobility” project (GA 290050), VIRTUAL VEHICLE is leading a consortium consisting of in total nine industrial (e.g. Daimler, PSA, LMS, AVL) and research partners (e.g. KU Leuven, Fraunhofer). Experts in this high-rated project offer dedicated doctoral training for 13 research fellows and provide the ideal environment for applied research in fields relevant for industry.

Driven by the need for a dedicated fundamental research in these multidisciplinary areas and following the successful evaluation of GRESIMO, KU Leuven and VIRTUAL VEHICLE joined the efforts and proposed another Marie Curie project – eLiQuiD.

The eLiQuiD (GA 316422), standing for “Best engineering training in electric, lightweight and quiet driving” has been submitted as a pilot project in a new implementation mode called European Industrial Doctorates (EID).

In this new implementation scheme, creativity, innovation and entrepreneurship in Europe is stimulated by involving businesses in doctoral training so that skills better match public and private sector needs. Each EID is composed of one academic institution and one participant from the private sector [1].

At VIRTUAL VEHICLE, three young eLiQuiD doctoral researchers are already working in the multidisciplinary field of NVH, lightweight design and electrified powertrain. One of the research tracks aims on development of a novel methodology for efficient modelling of the noise radiation by electric motor and its transfer into the passenger compartment.

An essential part of any scientific activity is the proper dissemination of the research outcomes. Besides the regularly organised public technical courses, the eLiQuiD consortium as an example of successful EID implementation has been selected by the European Commission for the footage of promotional movie. Both KU Leuven and VIRTUAL VEHICLE have participated in production of this video in collaboration with BBC Studios and Post-production.

The latest Marie Curie Action initiated by VIRTUAL VEHICLE is the BATWOMAN “Basic Acoustics Training - & Workprogram On Methodologies for Acoustics – Network” project (GA 605867). Again, this project adopts a multidisciplinary approach, in which it aims on establishing the links between different application fields in acoustics.

The consortium puts together eleven full and eight associated partners, all over the acoustic community. Automotive, musical and room acoustics experts provide dedicated doctoral training for young research fellows. The main objective is to establish new synergies between these three research fields in order to address the aspects of sound perception and sound quality as well as to consider the sound design issues in the full audible range.

Summary

The NVH related research and training network under the support of Marie Curie Actions Programme has been well established in Europe. VIRTUAL VEHICLE contributes to this network to a high extend and provides a training that goes far beyond university education.

The participation in Marie Curie projects enables professional cooperation and technical exchange not only between different consortium partners but also between the VIRTUAL VEHICLE research areas NVH & Friction, Mechanics & Materials and E/E & Software.

In Area NVH & Friction, these projects allow seven PhD students to push the limits for emerging NVH challenges.

References


Marie Curie Actions - Research Fellowship Programme

Marie Curie Fellowships are European research grants available to researchers regardless of their nationality or field of research. In addition to generous research funding scientists have the possibility to gain experience abroad and in the private sector, and to complete their training with competences or disciplines useful for their careers.

For further information on these projects, visit: [www.gresimo.at](http://www.gresimo.at) [www.fp7-eliquid.eu](http://www.fp7-eliquid.eu) [www.batwoman.eu](http://www.batwoman.eu)

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The acoustics of intake and exhaust gas systems affect the acoustics of the complete vehicle and thus the internal and the external noise. Based on current research results, a 1D simulation tool was developed at VIRTUAL VEHICLE that simulates the acoustic transmission behavior of the pressure pulsations in intake and exhaust gas systems and thus shows the acoustic properties at the design stage.

Nowadays, 1D CFD simulations are generally used in time domain for the simulation-based acoustic design and analysis of intake and exhaust gas systems. The necessary acoustic models of the individual components of the intake and exhaust gas systems are derived from the performance models for the design of the load changes in terms of performance, fuel consumption and emissions.

However, these adapted performance models are only suitable to a limited extent for the acoustic analysis of intake and exhaust gas systems and frequently lead to insufficient quality of the forecasting of the exhaust pipe noise level. In contrast, the newly developed method for the INEXAS tool uses models of all components present in the intake and exhaust gas system for the acoustic analysis. The calculation of the complete system depends on special calculation-efficient linear model formulations in the frequency domain, which are connected to one another over an acoustic network. Consequently, it is possible to conduct parametric studies considerably faster than in the time domain approach.

Turbocharger models for passive acoustic behavior

The simulation tool INEXAS developed at VIRTUAL VEHICLE can be used for various questions in the field of the acoustics of inlet and exhaust gas systems. The tool can investigate the acoustic properties not only of individual components (e.g. exhaust gas silencers), but also of the complete system. For example, the noise level from the exhaust gas outlet pipe of a complete exhaust gas system can be assessed.

Analysis of complex components in the complete system context

GUI (Graphical User Interface) for model construction and model parametering

Efficient Simulation Tool

INEXAS: A TOOL FOR THE ACOUSTIC DESIGN OF INTAKE AND EXHAUST GAS SYSTEMS
In particular, it is important to mention that a developed acoustic turbocharger model is available which depicts the passive acoustic behavior up to about 1.5 kHz very accurately. The passive acoustic behavior means the damping behavior of the pressure pulsations coming from the engine which flow through the components. Similarly, turbochargers and superchargers with many stages and variable or fixed turbine geometry can be modelled. The turbocharger model of VIRTUAL VEHICLE is based on a detailed description of the turbocharger geometry. For example, the description of the compressor consists of the following five parts (Fig. 1):

- Intake
- Rotor
- Diffuser
- Volute
- Outlet

Tangible simulation results

As an example, for exhaust pipe outlet noise level, the assessment of the overall level and individual classifications is currently the most commonly used method. In the future, it will be necessary to make virtual results better understandable in order to give simulation engineers more information and help them make better decisions for model modifications.

INEXAS makes simulation results immediately audible. When modifications are made to the model, the simulation engineer gets the corresponding audible impression immediately. Consequently, questions regarding the acoustic design can be considered in the early phases of development.

Flexible linking of measurement and simulation

In addition, INEXAS offers the possibility of including just one or several components of the intake and exhaust gas system in the simulation environment. As input data, the values of the acoustic transfer matrix are necessary, which can be determined using the 2-pole measurement method. In this way, complex systems (e.g. available exhaust gas silencers) can be acoustically designed and included in the simulation of the complete system.

Summary

INEXAS provides development engineers with an efficient tool for the acoustic analysis and design of intake and exhaust gas systems. The simulation tool features a graphical user interface for the model construction and for model parameterising. A specially developed acoustic turbocharger model enables the passive acoustic properties of the turbocharger to be investigated up to about 1.5 kHz for simple and multi-stage turbocharged systems with fixed or variable turbine geometry.

With INEXAS, simulation results can be made audible immediately, thereby providing engineers with an important additional aid for decision making when evaluating model changes. In addition, the measurement results of components that are present in the hardware can be included. Thus, even more complex components can be analyzed in the complete system context.

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ISNVH CONGRESS 2001 AND BEYOND: BACK TO THE FUTURE

The International Styrian Noise, Vibration and Harshness Congress - as if it had always been around. Based on an idea of key players in NVH research and development, the more or less local „Styrian Noise, Vibration and Harshness Congress“ became one of Europe’s leading NVH Conferences today. Wolfgang Wachmann went back in time to the very beginnings of the „SNVH“ to investigate how it became truly international.

There are quite a few fields of expertise in automotive engineering where Graz enjoys significant international reputation, research and development in automotive acoustics being certainly one of them. Fostered by their already existing close co-operation, leading industry players AVL and MAGNA teamed up with Graz University of Technology in the year 1999 to found the Acoustic Competence Centre (ACC) Graz.

One of the numerous results of this co-operation was the organisation of an international conference that aimed to analyse future requirements in the field of noise, vibration and harshness. The consortium behind the congress consisted of ACC, AVL, MAGNA STEYR Engineering and the Styrian Business Promotion Agency (SFG) together with the ACstyria Automotive Cluster. In 2006, ISNVH entered the co-operation with the Society of Automotive Engineers (SAE). After ACC and VIRTUAL VEHICLE merged in 2008, the partner network further spread.

All over the years, ISNVH also gained significant scientific profile: Hans H. Priebsch, then Scientific Head of ACC, supported the scientific content of the Congress from the beginning, and succeeded to install a peer review in 2006 for all published articles in cooperation with SAE.

Today, the ISNVH Congress can be considered as one of the leading events in the area of vehicle acoustics, vibration and friction in Europe, taking place bi-annually in Graz (Austria) and Michigan (USA).

2001: A Noise Odyssey...

“The advantage of comprehensive acoustic expertise – brought together for you in one single congress” – based on this credo, the first STYRIAN NOISE, VIBRATION & HARSHNESS CONGRESS (SNVH) took off in October 2001, focusing on “Integrated Vehicle Acoustics and Comfort”. ACC-CEO and Conference Chair Josef Affenzeller together with AVL-CEO Helmut List and Jürgen Stockmar (MAGNA) introduced their vision to the press: “This international conference aims to analyse future requirements in the field of acoustics. Specific NVH questions will be discussed, never losing sight of the total system of a vehicle. Furthermore, the integration of acoustics in the development process will also be discussed.” Still sounds very up-to-date – doesn’t it?

ISNVH History


J. Affenzeller at the 2001 evening reception

2nd SNVH 2003: J. Affenzeller, G. List, P. Piffl-Percevic

3rd SNVH 2005: Reception at Burg Graz
Right from the beginning, SNVH attracted key experts from industry and academia. The 2001 edition of SNVH featured chief acoustic engineers J. Tonhauser (BMW) and H.-E. Meier (DaimlerChrysler) as well as a keynote of M. Russell and lectures from W. Kropp (Chalmers), T. Petersson (TU Berlin) P. Sas (K.U. Leuven) and others. And, according to the records, Mr. E. Nijman (then CRF) was the first to submit his paper for review and is closely "related" to ISNVH since this very beginning...

2003: The future gets noisy?

"Acoustic Optimisation in the Vehicle Development Process of the Future" focused on the acoustic challenges in developing new cars. No wonder - the EC green paper on "Future Noise Policy" defined the vision for the year 2020 to “avoid harmful effects of noise exposure from all sources and preserve quiet areas”. But this challenge, however, can only be met by a systematic approach where the various paths from the noise sources to the outside world are considered. So again, leading experts from AVL, BMW, Continental, Daimler, Fiat, Ford, GM, LMS, MAGNA, Renault, Saab among others teamed up to identify new demands and offer new solutions.

One of the major improvements was very much appreciated by all participants: The congress moved its date from late October to the end of May – presenting Graz and Styria in best light to the international NVH community...

2005: Pushing the limits

"New technologies push the limits in vehicle acoustics" - from the 2005 SNVH perspective, recent research and development of new materials and technologies showed a high potential for new solutions in acoustics. Improved simulation procedures enabled developers to predict the acoustic behavior of a new design earlier in the development stage and in more detail than a few years ago. New experimental techniques and mathematical models improved the accuracy of assessing and predicting the behavior of noise-generating parts...

Some or all of that might’ve been the reason why the „usual suspects“ from leading OEMs and Tiers again came to Graz to get up-to-date insights from experts from Faurecia, fka, Goodyear, Vienna University of Technology and ZF, including lectures from P. Zeller (BMW) and R. Helber (DaimlerChrysler).

The extensive 2005 SNVH social and partner’s programme featured numerous highlights of culture and cuisine, landscapes and and landmarks - from Herberstein Castle to Styrian chocolate delights. And the questionnaire for the participants included this question: „Do you think organizing the SNVH Congress in the future jointly with SAE is an advantage?“ Well, as history tells us - many delegates thought so...

2006: Excellence on a global scale

Why wait for another two years to continue a success story? 2006 saw the 4th SNVH conference entitled „NVH Excellence – Achieving Results Beyond Customer Expectations“. Enhanced simulation procedures as well as new experimental techniques had been improving the prediction and assessment of the vibro-acoustic behavior of noise-generating parts. Now, the challenge was to validate the predictive quality and the accuracy of both simulation models and measurement techniques.

In addition to the presentations, a number of pre-congress workshops were held for the first time, aiming to increase the exchange of expertise in some technological hot spots. Furthermore, an international programme committee was established and SAE International joined as organizing partner for the first time, further strengthen SNVH as an important platform for information exchange in the global business of vehicle production and development. This might’ve been the point in history, where the SNVH Congress received it’s well-deserved “I” for „International“...

The impressive list of exhibitors, speakers and...
workshop leaders grew further, once again including Daimler/Chrysler’s H.-E. Meier, M. Abom (KTH), J. Manning (Cambridge Collaborative), J.-W. Biermann (RWTH), J. Meschke (Volkswagen AG), S. Bohlen (AUDI AG), F. Carosone (Ferrari), H.-M. Gerhard (Porsche), or J.-L. Guyader (INSA).

2008: Optimising NVH in Future Vehicles

Some years before, the discussion of environmental problems focused on exhaust gas emissions only. Now, noise started to be perceived as an equally substantial environmental issue. However, to reduce the exterior noise as necessary to avoid annoyance of the general public, ISNVH 2008 was looking for a holistic approach where road surfaces, tires and vehicles were treated in an integral view.

Experts from Bruel & Kjaer, FKFS, Fraunhofer, Microfrown or Volvo joined the 2008 issue of the congress - together with distinguished workshop speakers and chairs like W. Lauriks (KU Leuven), J. Delfs (German Aerospace Center DLR), B. Crouse (Exa Corp.), P.-O. Sturesson (GM) P. Göransson (KTH), M. Oswald (ANSYS Fluent) or N. Atalla (Université de Sherbrooke) - and, of course, a keynote from H. Hollerweger (AUDI AG). The holistic approach was underlined by various contributions, including remarks from A. Kaltenhauser (BMW) on conflict of objectives in future vehicle concepts regarding acoustic and lightweight design, or a widely recognized paper by B. Fachbach (VIRTUAL VEHICLE), introducing a „Concept of holistic vehicle design and optimisation for NVH requirements“.

2010: Ecology and economy

The 6th ISNVH called in international experts for „Sustainable solutions inspired by ecology and economy“ in times of heavy weather on the automotive markets worldwide. The critical solution of the international automotive industry required adequate solutions for both low cost and low emission products.

While hybrid and electric vehicles became of increasing importance, NVH engineers faced increasing demand to design light-weight vehicles with acceptable noise and vibration characteristics.

Top-ranking keynote speakers B. Pletschen (Daimler), P. Oliva (Michelin) and A. Kaltenhauser (BMW) and an impressive array of experts from industry and science, including J. Guggenmos (BMW), T. Bein (Fraunhofer), C. F. Hartung (Volvo), D. Schulze-Fehrenbach (Daimler), J.-W. Biermann (RWTH Aachen) or J. Affenzeller (AVL) contributed to a very successful congress.

2012: NVH and global markets

The 2012 ISNVH Congress under the title „Competitive NVH design and optimisation for the global market“ featured expert discussions about the latest challenges facing the automotive industry. The focus was on finding creative solutions for balancing the often conflicting demands for energy efficient and appealing lightweight vehicles on the one hand and high vibration and acoustic comfort levels on the other hand.

The growing variety of products requires high NVH quality in product development and production starting already at the component level and continuing right up to the finished vehicle. The 2012 ISNVH focused on reducing fuel consumption, decreasing pollutant and noise emissions, and hybrid and electric drives as a new field. Sophisticated high-tech solutions, as well as new technologies in vehicle acoustics came also from Graz from Virtual Vehicle.

The keynote speakers presented systematic insights into a wide variety of topics, including reduction of rolling noise (E.-U. Saemann, Continental), Zero Emission Vehicle concepts (S. Wang, Renault), sound sources and their transmission paths (J.-J. Ih, Korea Advanced Institute of Science and Technology) as well as the main gear noise problems of “Rattle and Whine“ (R. Singh, Ohio State University).
Exhibitors including AVL, Magna Steyr, Microflow Technologies, MSC Software and LMS Germany presented various technical products and software from the world of NVH. They found an excellent environment for sharing their ideas with their customers, as the conference offered the 180 participants and 22 exhibitors an ideal platform for networking and discussions with speakers and participants from leading NVH centers around the world.

2014: Future starts now!

So far, so good with this “hindsight about the past”. As this issue of the Virtual Vehicle Magazine has been produced to complement the 8th ISNVH Congress 2014, this pages might just have got you caught reading, distracting you from that key note speech or groundbreaking presentation on „NVH solutions for energy-efficient lightweight vehicles” right now and right in front of you…

Then again - if you missed out on this year’s ISNVH congress that would have given you a first-hand insight into the NVH present, please check out www.isnvh.com for our 2014 Retrospect and make sure to join us in Graz for the 9th ISNVH congress in 2016 to catch a glimpse of NVH future! ■

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SAVE THE DATE:
9th ISNVH Congress
June 22-24, 2016
Graz - Austria

9th International Styrian Noise, Vibration & Harshness Congress
The European Automotive Noise Conference

June 22-24, 2016  Graz / Austria  www.isnvh.com

During the last decade, the ISNVH congress evolved to be the European NVH event dedicated to mobility noise, vibration and harshness. ISNVH brings together engineers and specialists from industry, research centers and universities all around the world to discuss the latest technological innovations and recent achievements in vehicle NVH.

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Especially for premium cars the interior acoustic plays an important role for the drive comfort and drivers subjective perception of quality. This perception of quality can strongly influence the customer’s satisfaction and furthermore the purchase decision.

Possible sources of disturbing noise are vibrations caused by the chain drive. Therefore, the detectability of the vibration phenomena of the chain drive, as well as its interaction with the surrounding structure is getting more and more important. To be able to assess the influence of chain drives on the engine and the acoustics in early development phases, a method using 3D simulation models has been developed at VIRTUAL VEHICLE in close cooperation with the industrial partners BMW AG and IWIS motor systems and the scientific partner Loughborough University.

The chain drive acoustics

The main inner excitation mechanism in the chain drive is the polygonal action, which means that a chain lying on a sprocket forms a polygon rather than a circle due to the discretisation of the sprocket. The typical noise excited by polygonal chain drive action is called "chain whine". The so called polygon frequency depends on the number of teeth and the rotational speed of the sprocket. In general, the polygon frequency lies between some 100 and some 1000 Hz.

An early assessment of possible negative acoustical effects of the chain drive by excitation of surrounding structures can significantly reduce the costs for prototyping and for late changes in the layout of the chain drive and engine. To avoid acoustically critical excitations, resulting in the emission of noise, the chain drives has to be 'harmonized' with the surrounding structure. Therefore, a reliable simulation method for the determination of the dynamic behaviour of the chain drive considering relevant adjoining.

Simulation approach

The proper modelling of elastic components of the chain drive and of the relevant surrounding components is essential for the correct simulation of the dynamic behaviour of the system. Therefore, the dynamic FE-method has been chosen as simulation approach. In close cooperation with the project partners, the commercial finite-element software Abaqus with its integrated multi-body simulation tool (MBS) has been chosen to be the environment for the model development.

Challenges for the model development

While commercial simulation tools can typically represent the chain motion in two dimensions, the modelling approach developed at VIRTUAL VEHICLE works in full 3D with fully elastic consideration of the surrounding structure in arbitrary complexity.

Since fine elastic FE-structures require high simulation efforts in case of explicit finite element simulation, structures like the chain and the teeth of sprockets have to be modelled as multi-body structures. Commonly, only a few elastic structures like shafts are considered in dynamic chain drive simulations. To consider the fully elastic behaviour of arbitrary complex structures of chain drive components and the
surrounding structure, the new approach combines the MBS representation of the chain with an elastic FE-structure.

The focus in modelling of chain drive components lies on the correct prediction of the dynamic system behaviour based on the correct physical modelling of the occurring effects.

The main parameters that influence the system behaviour and hence the acoustic performance of the model are

- Stiffness and damping of chain, guides, shafts/sprockets, bearings and surrounding structure
- Inertias of chain, sprockets, plunger (tensioner) and tensioning guide
- Friction between chain-sprocket, chain-guides, chain link-sprocket
- Behaviour of tensioner: damping (leakage, ventilation) and stiffness (oil, spring)

Validation of the system

The method and the used models have been validated by means of measurements on a chain drive test rig at the industrial project partner iwis. Validation starts with a simple setup, in which the first chain drive only consists of two sprockets, a chain, one fix guide, one tensioning guide and one chain tensioner. The inertia on the driven sprocket is caused by the sprocket, the bearing, the sensors and their support. Even this simple system causes a variety of dynamic effects, which have to be considered in the model to get the correct representation of the chain drive behaviour. The model of the simple, low inertia drive is quite sensitive on modelling errors and therefore well suited for the validation process. This enables a validation of small details e.g. friction models.

Fig. 3 shows a waterfall diagram of the angular rotational irregularities as a function of the rotational speed and the frequency, and the dominant polygon order (measurements with bushing chain). Figures 4 and 5 show the comparison of simulation- and measurement results concerning the polygon order of the rotational irregularities at the driven sprocket (Figure 4: bushing chain; Figure 5 silent chain). The simulation shows good agreement with the measurement.

Summary

At the final stage the developed tool will allow a predictive assessment of the dynamic and acoustic behaviour of chain drives. This results in a decrease of the development time and costs, e.g. caused by prototypes.

The challenges in this project include the understanding of chain specific physical principles of high speed dynamics as well as the...
correct modelling of the friction and impact behaviour. A further task is the combination of multi body dynamics and finite element analysis.

Project Partners

Our industrial project partners, iwis and BMW, significantly contribute to the project by means of their inhouse knowledge on chain drives and the model validation tests at iwis. Prof. Rahnejat and his team from the University of Loughborough act as scientific partner and provide support in the fields of contact behaviour and contact modelling as well as in MBS.

After a follow-up project, where the outcomes of this project are further extended by increased model complexity and performance, the simulation approach shall find implementation in engine simulation at the industrial partners.

Finally we want to thank our project partners for the successful cooperation, especially Robert Mirlach, Dr. Christian Guist, Rainer Abelshauzer (BMW-Group), Dr. Thomas Fink, Michael Winzer, Jürgen Kessler and Marc Eder (iwis), who performed the measurements at iwis, as well as our scientific partner from Loughborough.

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Model-Based Systems Engineering (MBSE) as a paradigm shift in product development:

Today’s vehicles resemble highly complex mechatronic systems, which are to be optimized in regard to comfort, manufacturability, reliability, as well as energy efficiency and recyclability while implementing new technologies. To achieve the best overall solution interdisciplinary collaboration is required.

MBSE represents a set of methods and tools for the development of complex systems with a strong focus on modeling the system as a whole including the integration of all related disciplines. This so-called system model is used as the central information hub for analysis, design and verification tasks in the development process.

VIRTUAL VEHICLE supports the introduction and application of MBSE in enterprises by the following means:

- Identification and analysis of potentials and benefits in the application of MBSE
- Consulting and supervision in the adaption of development processes, development methodologies and IT infrastructure for MBSE introduction
- Development of an enterprise-specific MBSE environment (methodology and IT tooling)
- Coaching and training for users and managers

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Vibrations of the drive train affect traveling comfort, as well as the acoustics, dynamics and service life of a vehicle. Reliable data on the behavior of the full system is required in the early development phase to ensure efficient development of the vehicle as a whole.

Virtual development methods on the test bench

To assure even more efficient and cost-effective product development in the future, currently available virtual development methods must be further developed and optimally linked to experimental tools. However, this does not mean the separate parallel or series implementation that is still predominantly practiced today, but rather a joint approach to a combined development methodology.

Mastering challenges with a joint approach

Achieving an optimum symbiosis between calculation and testing requires real-time models that can map the phenomena to be examined and produce a high-quality result with the required computing efficiency. Vibrations of the drive train play a critical role here, as they affect the full-system behavior via the vibration comfort and dynamics.

The real-time capability and specified result quality can only be optimized by means of an in-depth understanding of the physical processes involved and the underlying mathematical relationships.

In a joint research project with AVL List GmbH, Gesellschaft für Industrieforschung mbH (Association for Industrial Research) and the Department of Mathematics and Statistics of the University of Konstanz, real-time drivetrain models for passenger cars were successfully developed and improved with respect to their computation efficiency. This joint research work focused on two components: the "hydrodynamic torque converter" and the "hydraulic engine mounting".

Real-time engine mounting model

The engine-transmission assembly of a vehicle is mounted elastically to the vehicle structure by means of the engine mounting, transmission mounting and torque supports. Some of these mountings must satisfy opposing requirements. Thus, a high damping efficiency is required in the range of low stimulation frequencies and at large amplitudes, whereas good insulation is called for in the high-frequency range and at small amplitudes. Because of these requirements, hydraulically damped engine mountings are almost exclusively used today.

In order to optimally damp the low-frequency rigid-body vibrations of the engine-transmission assembly, a hydraulic system consisting of an upper and lower fluid chamber and an inertia track is used. This system is integrated directly into the interior of the mounting (Fig. 1).

The analogous mechanical model of an engine mounting exhibits ideal rigidity and viscous attenuation of the elastomer body. The hydraulic system can be modelled in simplified form by means of standard differential equations (momentum and continuity equations).

The engine-transmission assembly can be considered as a rigid body in the relevant frequency range up to about 50 Hz. The basic mechanical equations (Newton-Euler equations) describe the position and orientation of this assembly in space based on applied external bearing reactions and drive torque.

Hydrodynamic torque converter for real-time simulations of the drivetrain

In addition to the extended engine mounting model combined with the engine-transmission assembly, a parameterized, real-time overall drive-train model was developed which includes extended sub-models for the hydrodynamic torque converter with a lock-up clutch and mechanical torsional vibration damper. In this model, the planetary gear trains in the automatic transmission are simulated in simplified form by means of two rotating masses linked via kinematic transmission. A gear change (up or down) is initiated by a switching characteristic, and the change from the current transmission ratio to the new one takes place as a continuous function during the defined switching time. The lock-up clutch of the torque converter is also controlled via a switching characteristic and can alternatively be operated in slippage mode via a PID control path.

The simulation of the high-frequency vibration phenomena in the drive train is based on an efficient real-time engine model designed to calculate the cyclically resolved crank angle deviation.

Fig. 1: Sectional view of a state-of-the-art hydraulically damped engine mount
The overall drivetrain model is designed for both motor and coasting mode and thus covers all typical operating conditions. The models are produced in Simulink, which ensures that they can be compiled and extended on standard real-time platforms.

Added value derived from innovative simulation approaches

Comparisons between measurement and calculation with the conventional spring-damper model (relating the force to the path it takes) and the real-time model taking the hydraulic system into account show a significant improvement in the simulation of low-frequency vibration phenomena in the drive train. For this purpose, measured path excursions at the mountings were examined during load change processes and compared with the test results.

Simple and efficient model parameterization

The simulation of vibrations in the drive system often involves model parameters for which insufficient test data is available. In many cases, such parameters are estimated on the basis of empirical values or from rough specifications given in the literature.

One methodology developed at VIRTUAL VEHICLE for the efficient parameterization of the developed engine mounting models in the relevant frequency range is based on test results obtained on the component test bench and thus permits fast and robust identification of the model parameters (see Fig. 2).

Summary

The drive train is already tested at an early stage of vehicle development to coordinate its drivability in hardware-in-the-loop environments. To simulate the vibrations, suitable models are required for the entire drive train in order to ensure real-time capability and meaningful results.

In a joint project with AVL, Gesellschaft für Industrieforschung and the Department of Mathematics and Statistics of the University of Konstanz, new models and methods for parameterizing two drivetrain components, namely the torque converter and the aggregate mounting, were successfully developed. The improved and optimized drivetrain models enable the simulation of relevant driving maneuvers designed to coordinate drivability while achieving improved results and the required computation performance.

THE PROJECT PARTNERS

AVL

Universität

Konstanz

GESSELLSCHAFT FÜR INDUSTRIEFORSCHUNG MBH

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SIGRID KLINGER Gesellschaft für Industrieforschung mbH
**FRICTION:**
Non-contact torque measurement of the MAN cam drive

In order to determine the power losses of an engine accurately, it is necessary to examine the torque, occurring at the camshaft, down to the smallest detail. In the course of a research project together with the industry partner MAN, the VIRTUAL VEHICLE developed a torque measurement system that can be integrated directly into the cam shaft. The system is supplied with power wirelessly and measurement data are provided in real-time.

The working group „Testing and Validation“ of the VIRTUAL VEHICLE is working intensively on the development of special measuring technology. Together with the experts from the area „Tribology and Efficiency“ and the industrial partner MAN a non-contact torque measurement system for the cam drive of the MAN D26 engine has been developed recently.

The minimal space was not the only special challenge in the development process but also the very high temperatures in the engine block. At temperatures above 70 °C, a battery for supplying power can not longer be used. Therefore, the project-team decided to feed-in energy via a non-contact induction-power transmission module.

The measurement of the torque is performed by strain gauges in a full-bridge circuit, which are applied in the camshaft. These strain gauges change the torque in the camshaft, generated by the torsions-shear stresses, into an electrical signal.

This signal is amplified on the autonomous measurement data acquisition VIFDAQ (also integrated into the camshaft), then evaluated and transmitted in real-time via Bluetooth to the measurement computer. Another feature is that the torque and temperature of the camshaft can be directly recorded by VIFDAQ.

The torque measuring system, developed at the VIRTUAL VEHICLE, is a further step to analyze and minimize the power losses in the engine as good as possible. The same principle for the torque measurement can be applied in many other applications, such as auxiliary components or crankshaft.

![Torque transducer before and after being integrated in the camshaft](image)

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**Worth reading!**

**AUTOMOTIVE BATTERY TECHNOLOGY**

VIRTUAL VEHICLE’s battery expert Dr. Alex Thaler and Head of Electronic-Department Dr. Daniel Watzenig present with their book “Automotive Battery Technology” new approaches of modeling in terms of battery integration in vehicles.

The book is part of a series edited by VIRTUAL VEHICLE and published by Springer Verlag.

Thaler, Alexander, Watzenig, Daniel (Eds.): Automotive Battery Technology
Springer, 2014

- Overview of possible approaches to model electrochemical energy storage systems in automotive industry
- New approaches for proper and detailed modeling of processes within the battery cell
- Methods are shown which will achieve an efficient and safe implementation of battery technology in modern vehicles
HYBRID SUB STRUCTURE TESTING

New material concepts require new sub structure testing methods. VIRTUAL VEHICLE introduces a novel hybrid sub structure testing method to replace full vehicle tests. By reproducing the same load on the B-pillar in sub structure testing as in the full vehicle with respect to deformation energy, speed and behaviour, this new method enables OEMs to significantly speed up the product development process, resulting in a reduction of prototypes and full vehicle testing.

Full vehicle model
- Reduction of the full model to relevant geometry information

Component test
- Development of rocker panel and roof connections
- Development of light weight barrier vehicle with new developed impactor

Analysis
- Reproduction of full vehicle boundary conditions

Comparison
- Comparison between numerical simulation and experimental data

Results:
- A new generation of sub structure testing
- Reproduces kinematics, deformation speed and the whole deformation of the full vehicle test
- Efficient numerical simulation model for development of the sub structure tests
- Significant reduction of prototype testing

Contact and Information:
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DEWI: Launch of EUR 40 Million EC Project

DEWI („Dependable Embedded Wireless Infrastructure“) is the latest major project striving to reinforce Europe’s leading role in the field of Embedded Systems. The project, led by the VIRTUAL VEHICLE, has a budget of 40 million Euros and involves 58 partners in industry and research from 11 countries.

What may have sounded like science fiction only a few years ago starts to become reality now and may soon be a natural part of our lives. Wireless systems, in particular wireless sensory and communication systems that are embedded within buildings, cars, trains and airplanes, will fundamentally change our everyday life. Such “Smart Wireless Solutions” are at the core of the EC project DEWI, which was launched at the 27th and 28th of March by the VIRTUAL VEHICLE.

The fundamental idea behind DEWI is the creation of a reliable, intelligent and distributed supporting environment. This world of DEWI will be outfitted with sensors, displays and other high-tech elements. Many of these elements are closely linked and integrated into everyday objects. However, many existing wireless solutions are not yet capable of replacing existing wire-based products in the market. Therefore, DEWI will focus on industrial and user needs.

DEWI is not concerned with fundamental research. Instead, it deals with 20 specific industrial use cases. About 150 researchers will be working on wireless sensor networks throughout the next 36 months. Results will be presented and demonstrated to the public across Europe.

7th GSVF: The Elite of Vehicle Developers in Graz

This May Styria was again Europe’s center for virtual vehicle development. For the 7th time more than 150 experts from research and industry met during the Graz Symposium Virtuelles Fahrzeug (GSVF), which was organized by VIRTUAL VEHICLE and Graz University of Technology.

The internationally renowned GSVF deals with future trends in interdisciplinary vehicle development for road as well as rail transport. A highlight of this year’s event was the lecture by BMW on the functional design of the electric vehicle BMW i3. Both the BMW i3 and also the Hybrid BMW i8 were presented in the exhibition area of the congress.

During the symposium more than 20 presentations have been given by international experts from industry and research - including BMW AG, Porsche AG, Volkswagen AG, Adam Opel AG, Audi AG, AVL List GmbH, Robert Bosch GmbH, IPK Fraunhofer or Karlsruhe Institute of Technology. The main topics of their lectures were the current challenges facing the industry in vehicle development, such as more complex drive systems, functional safety or the communication between vehicle and infrastructure.

By now Graz has established itself as a research magnet attracting international participants to conferences. „With events such as the GSVF, Styria positions itself as an important spot for automotive and rail development in Europe“, says Dr. Jost Bernasch, CEO of VIRTUAL VEHICLE.

www.dewi-project.eu

www.gsvf.at
SAVE THE DATES!

18th International ESAFORM Conference on Material Forming
April 15-17, 2015
Graz / Austria

www.esaform2015.at

The 18th International ESAFORM Conference on Material Forming – ESAFORM 2015 will be held for the first time in Austria and will take place at Graz University of Technology. The conference will cover numerous disciplines related to material forming including metals, polymers, ceramics and composites.

24th International Symposium on Dynamics of Vehicles on Roads and Tracks
August 17-21, 2015
Graz / Austria

www.IAVSD2015.org

The International Symposium on Dynamics of Vehicles on Road and Tracks (IAVSD) is the leading international conference bringing together scientists and engineers from academia and industry in the field of ground vehicle dynamics to present and exchange their latest ideas and breakthroughs.

8th Graz Virtual Vehicle Symposium
May 19-20, 2015
Graz / Austria

Complex future drivetrains, functional safety or the interaction of vehicle and infrastructure are only a sample of current challenges of vehicle development. More than ever a perfect collaboration of different disciplines is essential to solve these tasks successfully. The Graz Virtual Vehicle Symposium (GSVF) again will provide intensive exchange and discussions on experiences, prototypical solutions and actual tendencies in the field of interdisciplinary vehicle development.

9th International Styrian Noise, Vibration & Harshness Congress
June 22-24, 2016
Graz / Austria

During the last decade, the ISNVH congress evolved to be the European NVH event dedicated to mobility noise, vibration and harshness. The brings together engineers and specialists from industry, research centers and universities all around the world, to discuss the latest technological innovations and recent achievements in vehicle NVH.

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- Integrated Vehicle Development
- Simulation & test based Validation
- Interdisciplinary Methods and Procedures

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- Engine and Powertrain Optimization
- Vehicle Safety
- Hybrid Verification

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