Harley-Davidson's 100th Anniversary – The Sound of a Legend

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A high performance motorcycle using completely different engine architecture than traditional Harley-Davidson motorcycles was to be developed. However, to meet customer and corporate expectations, the sound of the motorcycle had to be reminiscent of the "Harley Sound." In addition, the intake and exhaust systems needed to provide high performance (115 HP) and style while meeting worldwide noise and emission regulations. Specifications for vehicle component noise source levels were developed at the start of the project based on regulatory requirements and corporate sound quality expectations. Acoustic and performance development of the powertrain, intake and exhaust systems proceeded based on theoretical modeling, lab and test track measurements. Several design iterations were investigated to optimize acoustic, vehicle performance and durability concerns while retaining essential styling cues. Finally, noise certification testing was performed to validate and homologate the vehicle for worldwide distribution.

You know it's a Harley as soon as you hear it, before you even see it. The throaty pounding and off-centered drumming beat are part of the signature sound that uniquely defines the persona of the machine and clearly differentiates the manufacturer from its competitors. Owners don't just want transportation to get from one place to another. They want a riding experience which, according to Harley-Davidson, is the sum total of the Harley 'Look,' 'Sound' and 'Feel.' One of the biggest parts of the riding experience is the classic sound of the bike. It's all about the "potato potato" rumble riders expect when they rev up the engine.

Few products have such a loyal following. The Harley Owners Group (HOG) numbers more than 660,000 in 115 different countries, making it the largest motorcycle enthusiasts club in the world. They certainly don't hide their passion for the machines or their demands that the bikes retain the characteristic sound these heavyweight motorcycles have had since William Harley and Arthur Davidson built their first one in 1903.

Since the early part of the 20th century, Harley-Davidson motorcycles have been renowned for their 45-degree air-cooled common crankpin V-twin motor. The sound of this engine configuration has become identified with the Company. In the mid-1990s, a group was assembled within Harley-Davidson to develop a motorcycle that would attract new riders to the Harley family. It was determined that high performance and handling would be essential to attract new or younger riders. Styling needed to be cutting edge yet identifiable as a Harley-Davidson.

At about this same time, the company was evaluating the marketing potential of the VR1000 race bike. This bike was designed specifically for Superbike racing and utilized a unique 60-degree V-twin engine configuration to accommodate the packaging and performance requirements for a Superbike. Making this race-only vehicle street legal would require a number of design changes to meet noise and emissions requirements. However the VR-based engine had the potential to power a high performance cruiser or street rod that could help meet the goal of attracting new riders to the brand.

Noise Specification Development

It was decided that a joint venture with Porsche Engineering Services would facilitate powertrain development for this program. This posed a challenge for NVH (Noise, Vibration and Harshness) development, as powertrain development was concentrated in Germany with the rest of the vehicle development occurring in the United States. The joint development effort required a detailed list of expectations and specifications to ensure successful integration of the vehicle components.

Work began on developing specifications for the vehicle. To be competitive with other future performance V-twins, output needed to be in the range of 120 HP at the crank. Although the 60-degree V-twin engine configuration of the VR was to be retained, the sound of this vehicle needed modification to be identifiable with the "Harley Sound" while still meeting noise emissions standards.

Noise specifications were developed to balance foreseeable regulatory requirements with customer sound quality expectations. Highlights of the major market noise regulations are presented in Table 1. Since more stringent European (EEC) noise limits were under discussion during the development of this vehicle, requirements to meet lower future regulations were considered during early development.

Customer sound quality expectations are not as easily defined as regulatory requirements. Years of research into customer preference,[1] along with listening to most bikes on the street, show that an exhaust dominant sound is preferred. Benchmarking of competitive vehicles along with current Harley-Davidson vehicles was performed at a component level. The major noise source contributors were defined as the intake, exhaust and powertrain (mechanical). It was determined that due to the 9000 RPM limit and proposed gearing, one intake and exhaust design would be able to meet all major market noise regulations without any excessive performance loss. Specifications were developed to stay within a pass-by noise budget of 80 dBA. Major component noise sources were:

- Mechanical ≤ 74.5 dBA.
- Intake ≤ 68 dBA.
- Exhaust ≤ 78 dBA.

NVH Development

The responsibility of the Harley-Davidson NVH Department is to "preserve and enhance" the characteristics identified as the Harley sound, all while improving performance with the latest design enhancements and continuing to meet strict domestic and international noise regulations and without compromising the Harley 'Look' and 'Feel.' This balancing act was clearly no simple task, since the company is constantly adding new technology to its designs to improve drivetrain and engine performance, ride quality, handling and durability.

For most manufacturers, it would be easy to put covers and cowlings over the powertrain to tailor mechanical noise or balloon up the intake and exhaust system to meet regulatory noise requirements. In fact, many of Harley's competitors do just that. But hiding the engine and other systems would violate the Harley 'Look.' So instead, the sound must be engineered into the machine – sculpting the noise to produce just the right balance of tone, pitch and beat from the intake, exhaust, engine and drivetrain.

To meet both performance and noise specifications of the new design, large intake (Figure 1) and exhaust system volumes would be needed. This required a different approach for packaging than on traditional Harley-Davidson motorcycles. Early cursory calculations, one-dimensional computational fluid dynamics (CFD) modeling and prototype evaluations using a

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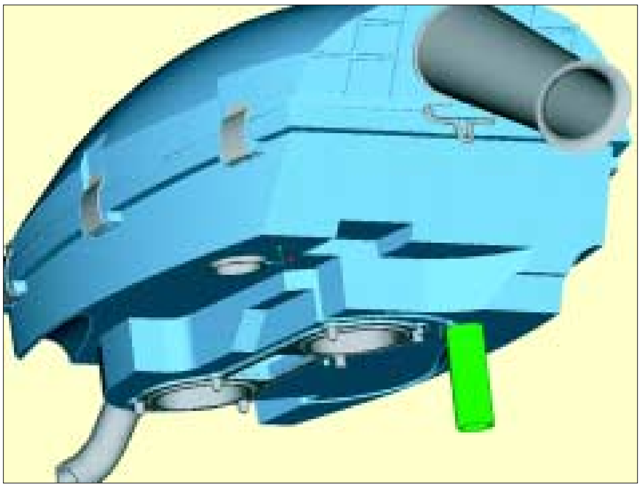


Figure 1. Intake silencer model.

VR1000 race engine (on the race team's dyno!) were used to derive a 10L intake and 12L exhaust volume specification.

Intake Development. Details of the intake development are presented in Table 2. The large (10L) intake requirement immediately conflicted with the traditional Harley-Davidson right side intake due to ergonomic and styling concerns. Packaging an exhaust system almost 3 times the size of traditional cruiser systems challenged the handling, ergonomic and styling concerns of the vehicle.

To optimize performance and packaging, the intake was located on top of the engine. An expansion chamber-type airbox with forward facing inlet was utilized to maximize performance and aid noise compliance by further separating and distributing the component noise sources.

Theoretical acoustic and performance models were verified with flow and acoustic insertion loss measurements. Extensive dynamometer testing was performed to optimize the length and shape of the velocity stacks to balance performance and packaging concerns. Dyno performance along with pass-by and stationary noise measurements were used to optimize the inlet diameter, length and splay of the air box inlet (snorkel) and sealing system.

Exhaust System Development. To develop the exhaust envelope, numerous packaging configurations were analyzed from an acoustic, performance and styling perspective. Extensive computer as well as physical clay modeling were used to develop the complex, expanding but still curvaceously shaped envelope to address all of these concerns. To facilitate manufacturing and assembly, a 3-component muffler system was derived. This combined a front and rear cylinder crossover and attenuating elements in a pre-muffler or auxiliary volume along with an upper and lower muffler.

As with the intake, cursory calculation and CFD modeling were utilized to develop the initial exhaust volumes and internals. These were verified using simplified conical prototype components on a "test buck" or development vehicle powered by a VR1000 race engine (Figure 2).

Several internal configurations were analyzed throughout the exhaust system development. Initial auxiliary volume prototypes showed that shell radiated noise limited system attenuation and provided unacceptable sound quality. Subsequent configurations incorporated a header pipe crossover located in the front portion of the auxiliary volume to maximize performance by allowing each cylinder to use both muffler volumes. Shell radiated noise was reduced by optimizing the gauge of the steel of the outer shell along with implementing internal shell damping by constraining fiberglass insulation between the exterior shell and the internal crossover. Exhaust outlet attenuation was increased with minimal performance degradation by implementing a Helmholz resonator in the gas flow path after the crossover. Emission regulations in some markets required that a catalyst version also be developed.

To maximize performance and noise attenuation, a tri-pass

State-of-the-Art NVH Development Facilities

Harley-Davidson's commitment to sound quality and regulatory compliance in its products is evidenced by the company's investment in a state-of-the-art NVH Development Center, a part of the Willie G. Davidson Product Development Center in Wauwatosa, WI, just outside Milwaukee. Completely closed to the public as well as most of the non-engineering personnel at the company, the first stage of the secure facility was completed in 1997 as one of the premier NVH test facilities in the world.

The lab includes a fully anechoic chamber for engine and transmission studies as well as a semi-anechoic chamber with a 160 HP chassis-dyno for full vehicle testing. These test cells are equipped with automated-sequence, remotely-controlled arrays of microphones for gathering acoustic-intensity and acoustic-holography data while sensors record engine vitals, vibration levels and a host of other test-related information.

The facility also has a jury listening room where people from across all disciplines in the company are selected to assess sound quality of proposed designs, thus providing a correlation between rider preferences and product performance. (Editor's note: For more on jury testing, see the S&V Observer on page 6.) Harley utilizes experienced riders throughout its organization for jury testing, including senior management, accounting, marketing, sales, engineering and shipping. A good cross-section better reflects the range of opinions and preferences found in potential customers, while off-site jury tests with current customers are also used to validate the process.

Table 1. Summary of major market noise regulations, dBA.

Noise Regulations	Limit	Notes
USA Pass-by: 45-55% HP accl., 50 ft.	80	No averaging
EEC Pass-by: 2nd & 3rd gear, 50 kph accl., 7.5 m	80	1 dB correction, avg. 2nd & 3rd
Australia Pass-by (EEC procedure)	82	Same as EEC
Australia Stationary: 50% peak, 0.5 m @ 45˚	94	
Japan Stationary: 50% peak, 0.5 m @ 45˚	99	

Table 2. Early intake volume vs. measured noise vs. performance calculation results.

Intake Volume	80 dBA: int. = 77 dBA	77 dBA: int. = 67 dBA
9.3 L	–	120 HP
8.5 L	–	110 HP
7.8 L	120 HP	101 HP
7.0 L	107 HP	90 HP
6.5 L	100 HP	84 HP
6.0 L	92 HP	77 HP
5.5 L	85 HP	71 HP
5.0 L	77 HP	65 HP

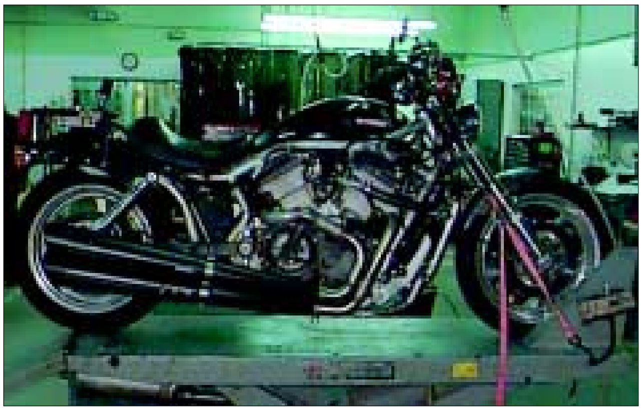


Figure 2. Early development exhaust system on VR1000 powered "test buck."

muffler design was utilized. The muffler elements were optimized to balance performance, acoustic and assembly concerns. The muffler internals utilize nested D-shaped tubing to facilitate manufacturing and assembling the internal components into the complex shaped muffler shells. Styling criteria dictated different lengths for the upper and lower mufflers, resulting in many unique parts with different tunings and cross-flow for the two mufflers.

Mechanical Noise Development. Powertrain development was concentrated at Porsche Engineering Services in Germany by a joint team of Porsche and Harley-Davidson engineers. Examples of Porsche and Harley-Davidson pass-by test vehicles are shown in Figures 3 and 4, respectively. As part of the specifications for the vehicle, a single balancer and rubber mounting were prescribed for the powertrain. This was to minimize

Figure 3. Porsche mechanical noise source pass-by test vehicle.

chassis component noise contribution and also to enhance vibration quality of the vehicle at all RPM ranges. To ensure compliance with the 74.5 dBA mechanical noise objective, Harley specified helical transmission gears along with a high contact ratio primary drive. To ensure noise development was consistent between the Porsche and Harley-Davidson design teams, pass-by noise results between Porsche's and Harley-Davidson's facilities were validated to be within 1 dBA. This was determined by measuring a vehicle at Porsche's pass-by noise test track and then shipping the vehicle, as tested, to Harley-Davidson's test track and repeating the measurements.

Sound Quality and Component Noise Evaluation

Subjective sound quality analysis was used along with regulatory whole vehicle and component testing to evaluate overall and component noise sources throughout development.

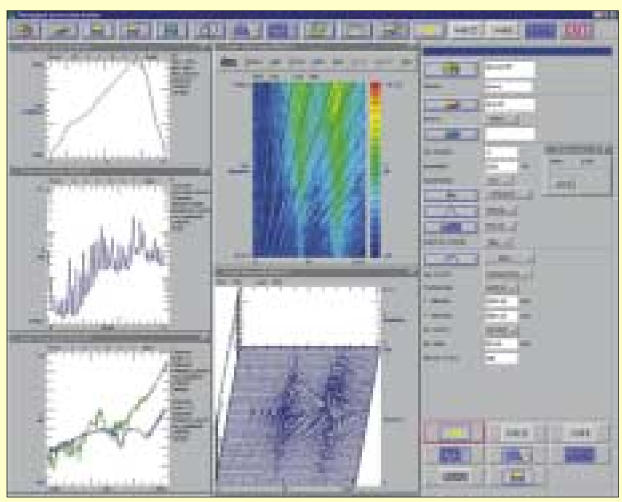
NVH Software Profiles

For its NVH work, Harley-Davidson uses a range of software from LMS International including CADA-X for acoustic and vibration testing, SYSNOISE for predicting and visualizing sound envelopes, and general utility programs FMON and TMON to correlate data and perform a variety of comparative studies.

LMS CADA-X system is a complete platform for test-based acoustic and vibration engineering. The system is based on a choice of multichannel measurement front-ends, runs on PC and workstation platforms, and has all the standards and hooks to connect to a variety of dedicated testing hardware, such as smart sensors, laser vibrometers, remote-controlled microphone arrays and chassis dynamometers. The modular software ranges from general-purpose multichannel data acquisition and DSP through basic and advanced acoustics, signature testing and operational analysis, structural testing and modal analysis. This flexible system has met the needs of Harley-Davidson's most sophisticated engineering tasks and is scalable to the operational needs of the test technician, the development engineer or the structural analyst.

LMS SYSNOISE is used for vibro-acoustic design, troubleshooting and optimization. From predicting the sound inside a cavity to estimating the sound field around a structure to calculating the structural response to an acoustic load, SYSNOISE has helped optimize the vibro-acoustic performance of many Harley-Davidson motorcycles. Over the years SYSNOISE has been used and validated on a wide range of vibro-acoustic product design applications. It is ideal for interior acoustic analysis of passenger compartments, acoustic radiation prediction of engine/powertrains, back-scattering analysis of underwater vessels and acoustic transmission analysis of wall partitions, doors and seals.

LMS Fourier Monitor (FMON) is utilized for Harley-Davidson's structural testing situations and is seamlessly integrated into tools for set-up design, modal analysis and FE



Typical LMS CADA-X display.

correlation. It features superb on-line graphics, "on the fly" testing changes and efficient productivity tools. FMON incorporates the feedback of a wide user community and is backed by ISO 9001 certified quality procedures for product development, maintenance and support.

LMS Time Data Processing Monitor (TMON) allows the integration of existing data manipulation methods (data import, conditioning, analysis and documentation) into one familiar, network-able environment. It has the raw power to satisfy Harley-Davidson's requirements; the displays are nimble and responsive; advanced functionality is balanced by an easy interactivity; and it has an extensive set of productivity tools. TMON has a proven performance and is backed by ISO 9001 certified quality procedures for product development, maintenance and support.

Figure 4. Harley-Davidson mechanical noise source pass-by test vehicle.

Although Harley-Davidson utilizes several objective metrics[1] to evaluate traditional product sound quality, the unique configuration of this engine made the relevance of the existing metrics questionable for this vehicle. Sound quality evaluation was a critical path for the development of several components and systems including the tooth profile of the primary gears, the fuel pump and its mounting system, the idle speed of the vehicle, the primary drive anti-backlash gear (Porsche) and the exhaust system.

Extensive component pass-by noise analysis was used throughout this project to determine major noise source contribution for regulatory requirements. This was performed by covering and uncovering mechanical and chassis components with mass loaded vinyl barrier sheeting. Intake and exhaust source contribution was determined by comparing exposed components with silenced ones using large volume external intake and exhaust silencers, in addition to barrier coverings. The component source levels were determined by subtracting the silenced from the exposed component measurements. One set of test results is shown in Figure 5.

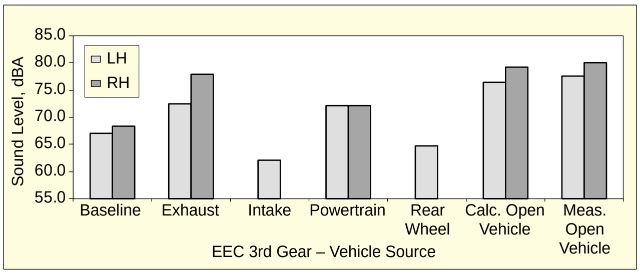


Figure 5. 3rd gear EEC pass-by component and vehicle noise source levels for a 2002 Harley-Davidson VRSCA.

Figure 6. Production Harley-Davidson VRSCA "V-Rod."

Conclusion

Precertification testing was performed on the final prototype vehicles for verification before official homologation testing. This led to additional noise source evaluation of gear tooth profiles as a result of last minute supplier issues. Finally the vehicle was ready for launch. A pre-production build of vehicles, using production parts, produced final validation and certification vehicles. Noise, emissions and a number of other tests were scheduled and witnessed by a registered test agency. Regulatory testing was successfully completed and the Harley-Davidson V-Rod motorcycle was now ready for full production (Figure 6).

Successful certification showed that major component noise source specification is valuable in facilitating joint development of motorcycle noise levels. This case showed that intake and exhaust system development could be performed halfway around the world from the powertrain with the desired end result. In addition, the resulting sound has been deemed reminiscent of the 'Harley' sound in many reviews by the motorcycle press.

Acknowledgments

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