DYNAMOMETER FOR TESTING HIGH-FREQUENCY NOISE OF DISC BRAKES

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1. INTRODUCTION

Even if every noise during a vehicle test is recorded with a data acquisition device, the majority of the release procedures of a new brake system - at least in Europe - are based solely on the subjective noise ratings of the drivers during a vehicle test. The best known tests for researching the brake noise in road conditions are the Los Angeles City Traffic test (LACT) in urban conditions in the United States and Mojacar test in Europe. The length of Los Angeles City Traffic test is normally 5000 miles or 8000 km. An average of 250 miles or 400 km is driven per day. Some tests might run for more or less days than the normal 20 day length. On average, the number of braking per mile is 4 to 5. This is a slightly higher brake application rate than normal city traffic. As a result of years of experience, this test was unanimously accepted between automotive manufacturers and their suppliers in the United States. These vehicle tests can fully assess the actual brake noise performance and are very representative in terms of the end customer perception. However, all of these vehicle tests are expensive, time consuming, and usually occur too late to affect any structural changes if noise is detected on a test vehicle brakes. That's why the leading manufacturers have developed laboratory dynamometer tests that can shorten the brake noise development cycle and provide accurate and objective statistical data to evaluate brake noise performance. Results from the laboratory can be used to quickly affect the structural changes to optimize the brake noise performance.

Besides dynamometer tests, non-contact measurement techniques-laser metrology can be performed in laboratory conditions too. Holographic interferometry, Electronic Speckle Pattern Interferometry (ESPI) and laser Doppler velocity measurement are methodologies that are used to identify the cause of the brake noise and for evaluation of engineering solutions [1].

1.1 *Holographic interferometry*

Holographic interferometry is a proven technique for the measurement and analysis of the absolute displacement, both out-of-plane and in-plane, of a disc brake generating noise. The standard holographic interferometry technique has been developed such that both separate dynamic images of the in-plane and out-of-plane vibration, together with the combined dynamic image indicating absolute displacement can be represented. The technique makes use of a series of time-related holograms recorded from three different viewing perspectives of the brake. Each image records absolute displacement, but as each of the three holograms view the brake from a different viewpoint then each comprises varying degrees of out-of-

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plane and the in-plane vibration, dependant on their angular position. This varying degree of displacement allows their manipulation in order to identify and isolate the in-plane and out-of-plane contributions to the overall excitation so that each may be considered separately. The out-of-plane is represented as a three-dimensional image whereas arrows represent in-plane amplitude as a "quiver" plot. The results show that the disc modes are extremely complex for caliper brake system and further suggest that the in-plane vibration amplitudes are much larger in magnitude than out-of-plane vibration amplitudes.

The laser metrology has unique advantage and can be applied not only in case of body/chassis and power transmission, but also in research of complex issue of the brake noise. Engineers can find out information about basic causes of the noise and vibrations and provide guidelines for the optimal design [2].

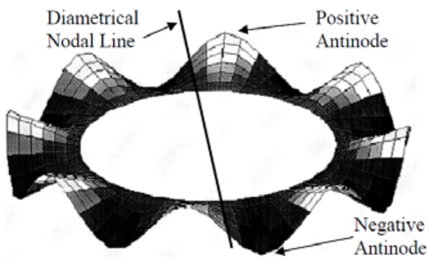
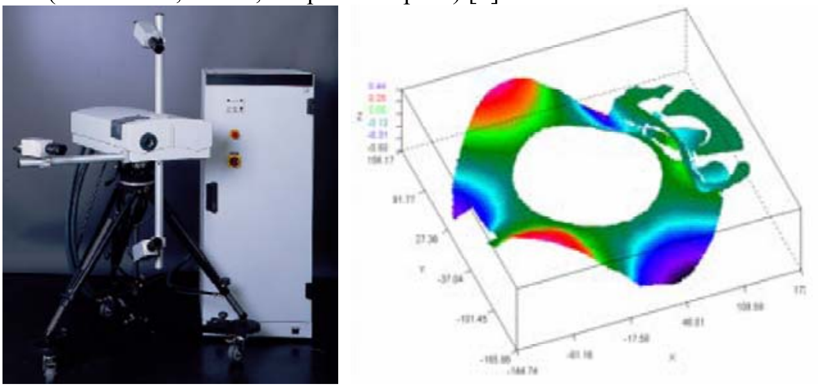


Figure 1: *Out-of-plane Vibration of a Brake Disc 8-Diameter Mode Order [2]*

Disc brake noise is generally associated with a friction pair of pad and disc. The vibration modes and natural frequencies have generally been associated with noise frequencies and there is strong evidence that the brake noise frequency is related to a specific natural frequency and out-of-plane mode of vibration of the disc - the frequency typically observed to be slightly lower than the corresponding free-free frequency. Previous research has mainly concentrated on the out-of-plane modes of vibration, where the disc is seen to exhibit purely diametrical modes of vibration, as shown in Figure 1. Therefore it can be said that there is a much greater appreciation of the contribution of out-of-plane displacement in a noisy brake system than in-plane displacement. The recent recognition of researchers to accept the importance of in-plane vibration during noise generation has therefore called for new techniques to be developed that enable complete field three-dimensional measurement [2].

1.2 *Electronic Speckle Pattern Interferometry*

In the area of structural testing, optical techniques have been successfully applied to the determination of dynamic response of the structure. Recently ESPI systems (Electronic Speckle Pattern Interferometry) using pulsed lasers are increasingly being used to replace conventional double pulse holography interferometers, and take not only the main advantages of holography relative to conventional measuring techniques, such as non-contact, full field measurement and sensitivity, but also use modern high speed cameras and computer techniques to capture and process the image (Figure 2). The ability of the pulsed ESPI has been further extended to the 3D measurement of dynamic response and modal analysis of vibrations. An important area of application is the field of the analysis of brake discs, with pulse ESPI systems providing complete maps of any component vibration during braking test (brake discs, drums, calipers and pads) [3].



a) *b)*

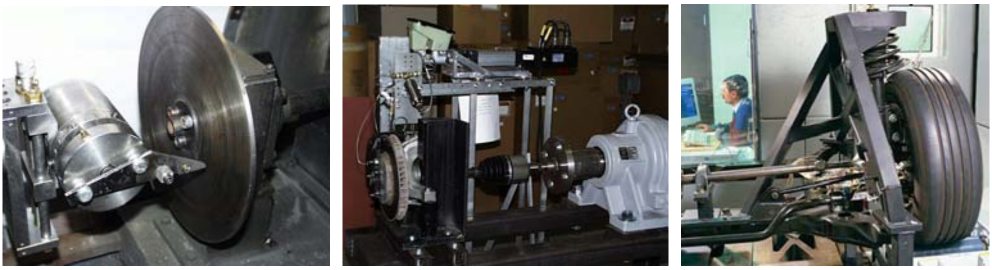
***Figure 2**: a) 3D-Puls ESPI System Q-600 b) Vibration mode of disc brakes [3]*

1.3 *Laser Doppler velocity measurement*

Scanning Laser Doppler Vibrometer - SLDV has some advantages over other measurement techniques because it is easy-to-use, applies low-power laser, has high spatial resolution, and it is non-contact technique. It can be used for the measurement of mode shape of components (rotors, pads and calipers) and modes of components/system. Operational Deflection Shape - ODS, or more precisely Instantaneous Squeal Mode- ISM of brake system rotor can also be recorded when the ISM is non-traveling mode. The procedure can be described as follows. When the microphone/acceleration sensor receives high-amplitude signal of single-frequency squeal/vibration, it sends a signal to the laser vibrometer to get it scanned. When the squeal disappears, scanning stops. This requires that an occurrence of squeal event takes a few minutes, which can be implemented with the brake dynamometer or drag vehicle test at a constant speed. Three-dimensional ISM can be obtained by combining the two laser heads/sensors for simultaneously scanning [4].

Disc brakes noise tests can be classified according to *the object of investigation*: the needle on the disc, the real disc brakes and disc brakes system with tire and suspension, Figure 3.

These test methods represent phases of approach to real structural connections of the braking system on the vehicle and the probability of generating a squeal in the case shown in Figure 3c) will have the greatest coincidence with the results in real road conditions.



a) *b)* *c)*

***Figure 3**: a) Pin on disc b) Disc brakes c) Disc brakes as part of the vehicle*

2. DYNAMOMETER

The objective of a brake noise dynamometer test is to reproduce the conditions and the noise that comes from the brake on the vehicle in motion. There have been many different approaches to this task, but the modern brake dynamometers are relatively similar in concept and operation. The current designs can be divided into two basic types. There is a brake or shaft-type dynamometer that drives the brake assembly from a shaft. The second category is a chassis dynamometer, in which a driven road wheel is used to drive a tire that drives the brake assembly.

2.1 *Shaft-type dynamometer*

Earlier noise dynamometers designed to reproduce brake noise were designed to performing only drag tests. These dynamometers did not have any means to represent vehicle inertia. With the implementation of SAE J2521 (SAE -Society of Automotive Engineers) [5,6], the first internationally recognized brake noise test procedure, these dynamometers were outdated. This test procedure requires both drag and regular stops. The application of inertial mass often gives smoother operation at low speeds, when the noise problems often occur. A typical example of such shaft-type dynamometer is shown in Figure 4 [7].

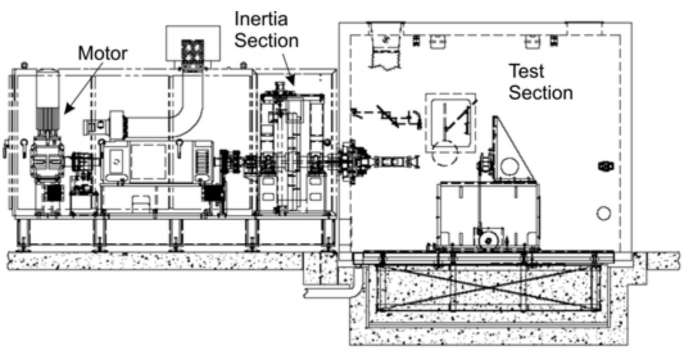


Figure 4: *Shaft-type brake noise dynamometer [7]*

2.2 *Basic Dynamometer Configuration and Operation*

An electric motor is used to spin the brake. For the modern automotive dynamometers the motor with power range from 75 to 300 kW is used. To perform realistic simulation of stopping a vehicle, the effect of the inertia of the vehicle must be represented. This can be done in two ways. The traditional approach is to use the discs on rotating shaft whose rotation inertia is equivalent to the linear inertia of the vehicle. A more recent approach is to use the electric motor to simulate the inertia of the vehicle. Modern brake dynamometers can provide both methods in order to give the user maximum flexibility in the simulating the vehicle braking system.

In order to test a wide range of vehicles it is necessary to simulate a range of inertia. The earliest approach to this problem was to provide a different inertia discs that can be manually mounted and removed on the dynamometer shaft. This is still done today on many dynamometers. In some dynamometers the inertia discs are automatically mounted and dismounted to the shaft. Depending on the size of the vehicle and the inertia increment being represented, these discs may weigh from several hundred to several thousand pounds.

Modern computers have enabled the simulation of the vehicle inertia through the control of the driving electric motor. Although for a number of reasons it is desirable to have at least one inertial disc on the dynamometer, it is now possible to provide extremely fine inertia increments and values above and below that physically mounted on the dynamometer with electrical simulation. There is a simple formula for predicting the amount of inertia that may be simulated on a particular machine [8]:

$$I_o = \frac{9549{,}3 \cdot P_m \cdot R_r}{a \cdot g \cdot \Omega}, \qquad (1)$$

where

a	- vehicle acceleration [m/s2],
g	- gravitational acceleration - 9,81 m/s2,
I_o	- available inertia [kg·m·s2],
P_m	- maximum engine power [kW],
R_r	- rolling radius of the wheel [m],
Ω	- rotational speed of interest [rpm].

Whatever method is used, the goal is to match the vehicle inertia as closely as possible to assure the accurate reconstruction of the stop. Precise match will ensure that the brake under test sees the same torques, stop time, temperatures, and number of revaluation as seen on the vehicle.

It is also necessary to match the other operating conditions of the braking system as mentioned above. One such condition is the pressure applied on the brake. Not only is it necessary to match the application pressure using the same brake fluid as employed in the vehicle, but it is also necessary to provide the same rates of pressure application. In some cases, squeal can be sensitive to the rate of brake application or brake release [1].

Of course, all the same brake components must be used in dynamometer squeal testing as are used on the vehicle. The problem is in defining how far the match must extend. There is a clear agreement that the principal brake hardware must be the same. This includes brake pads or shoes, the caliper or drum, as well as their components.

The controversy occurs when one talks about the influence of the rest of the vehicle. Some researchers believe that it is necessary to include the impact of entire suspension system and the tire and wheel attached to the brake with the tire rolling on a surface at realistic vehicle loads. There is a general consensus that it is necessary for low-frequency noise. However, for high-frequency noise, such as squeal it is not clear that this is required. Requiring the tire rolling on a surface at regular vehicle loads requires a major change in dynamometer configuration. As can be seen in Figures 5 and 6, one can still have a basic shaft-type brake dynamometer with a roll added, or it may be necessary to go to a chassis dynamometer in which the vehicle or a vehicle corner is operated on a dynamometer [7].

A drawing of a passive roll dynamometer is shown in Figure 5. In this case, the road wheel may be removed for testing without the tire end wheel. With these dynamometers, the roll is said to be passive because it is being driven by the tire that is driven by the dynamometer shaft. As will be discussed later, the second approach is to use a chassis dynamometer in which the roll is driven (Figure 6). For squeal testing it is generally agreed that one should include the full suspension systems of the vehicle corner on the dynamometer.

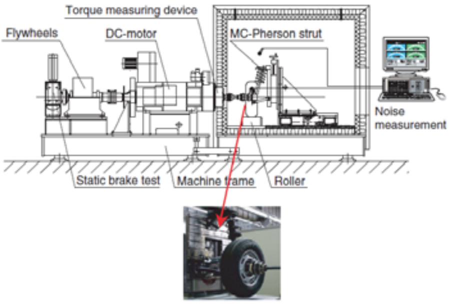


Figure 5: *Inertia Type Brake NVH Dynamometer [7]*

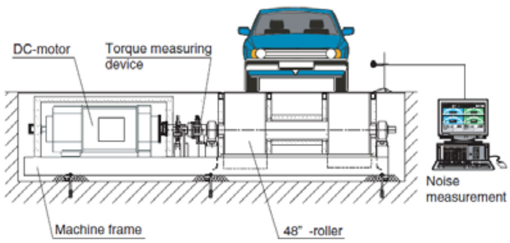


Figure 6: *Chassis Type Brake NVH Dynamometer [7]*

The environment in which the brake is operating is also important to reproduce the noise found on the vehicle. This includes both the acoustic environment and the environmental conditions. Acoustically, the environment of the vehicle operating on the road must be reproduced. This means an essentially free acoustical field above a reflecting plane. At the frequencies of concern, the road surface acts much like a reflecting plane. Otherwise, the brake sound energy is free to radiate with little impedance in all other directions. To approximate the free acoustic field in which a vehicle operates, the walls of the test enclosure are lined with an acoustically absorptive material. Materials used include glass fiber mats, mineral wool, and acoustic foams. Since squeal noise is defined to occur at frequencies of 1000 Hz and higher, the absorption of these materials is most important above 1000 Hz. A good approach is to maintain an absorption coefficient of 0.8 or higher above 500 Hz. This enclosure will have a floor of steel, concrete or other acoustically reflective surface. Such floors should approximate the acoustic characteristics of actual road surfaces [1].

To provide a sufficiently low background sound level to detect squeals, the walls of this room are also designed to provide very high sound transmission loss. Usually these rooms provide the background sound level below 50 dB (A). Double-wall construction is used to achieve the sound transmission losses necessary to assure sufficient transmission loss. Figure 7 shows the typical construction of chambers for recording brake noise [9]. In this case, two steel plates separated by 5 cm of foam or glass fiber insulation. Over the frequency range of interest, sound transmission losses of over 30 dB can be achieved.

As with any sound enclosure, it is crucial that flanking paths and seals at the door opening receive careful attention. If the enclosure is connected to the structure of the dynamometer of the laboratory floor on which noisy and vibration equipment are operating, all the work of careful enclosure design can be ruined. For more information on enclosure design, see [9,10,11].

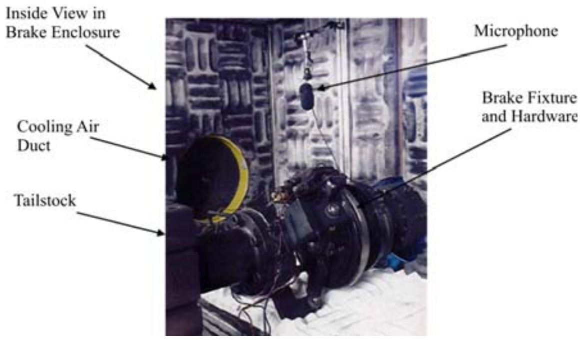


***Figure** 7: Typical Design of Sound Insulation [9]*

2.3 *Environment Control*

It is also necessary to represent accurately the environmental conditions under which the brake is operating. This may include both the temperature and relative humidity conditions. Later models of dynamometers provide the ability to control these parameters.

A problem that often arises is what is called "morning sickness". This condition occurs when the vehicle is parked outside overnight in the fall and winter months. The humidity rises overnight and may be higher than 90 % in the morning. At the same time, the temperature may drop to near freezing temperatures or below. These conditions of low temperature and high-humidity often encouraged squeal. In some cases, customers are experiencing noise under this scenario, when it is not noticeable under any other operating condition [1].

With an increasing awareness that environmental conditions can play a key role in squeal generation, most new noise dynamometers include systems to control the air temperature and relative humidity at the brake. Additionally, many manufacturers of components and vehicle manufacturers are clearly specifying environmental conditions that must be maintained during the noise test procedure. It is anticipated that these requirements will become more common.

2.4 *Data Acquisition and Control*

A critical part of the dynamometer system is the control and data acquisition system. A sophisticated control system is required to achieve the desired operating conditions and match the requirements of the current test procedures. The control system is required to follow prescriptions for the control of braking pressure, deceleration or braking torque. There may also be protocols setting desired starting temperatures and changes in pressure, speed, or other factors during the process of stopping [1].

To understand the occurrence of squeal properly, it is important to collect a large amount of experimental results. First the noise data must be acquired. In some instances this is as simple as collecting the data from a single microphone. In other instances, it may mean acquiring data from multiple microphones, accelerometers, and even laser Doppler vibrometers and optical holography systems. Often an accelerometer is located on the brake assembly for measurements of vibration in addition to noise. The data from the accelerometer can be compared with data from the microphone to determine whether the suspected squeals are from the brake and not extraneous noise from the dynamometer. In some cases coherence and coherent outpour power calculations are used for this assessment [12].

For the presentation of the actual vehicle operation and speed, the transition between tests, cooling air flow is typically provided to the brake assembly on the dynamometer. During normal operation of the brakes on the vehicle, especially at higher speeds, there is air flow over the brake that provides significant cooling. Furthermore, when the Initial Brake Temperatures - IBTs are specified, the cooling air allows faster cycles between tests. For instance, when an initial temperature of 50°C is specified, the next test may be at an initial temperature of 75 °C. Unfortunately, the 50 °C test may heat the brake at to over 200 °C. One can simply wait for the brake to cool down as a result of natural convection or, using cooling air flow, one can cool the brake to 75 °C in a few minutes.

During the noise test, it is important to record all the brake operating conditions to understand properly what was going on when the noise occurred. Typically this will include measurements of the brake pressure, one or more temperatures, speed, sound pressure levels and vibration amplitudes.

3. LABORATORY TESTING OF HIGH-FREQUENCY NOISE OF DISC BRAKES

Brake noise dynamometer developed in the Laboratory for testing the IC engines at the Faculty of Engineering in Kragujevac is shown in Figure 8. It is possible to comprehend the effects of vehicle inertia, due to the disc that is mounted on the rotating shaft. Disc's inertia is equivalent to the linear inertia of the vehicle, thus ensuring stable operation at low speeds that are relevant in terms of brake noise.

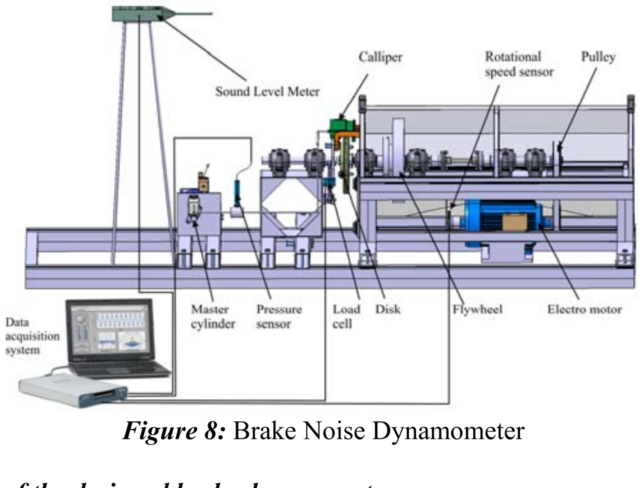


Figure 8: Brake Noise Dynamometer

3.1 *Description of the designed brake dynamometer*

Brake noise dynamometer consists from following functional units:

- Test bench with electric motor, power transmission and disc,
- Electric power installations,
- The installation for activation of disc brakes *i.e.* applying the braking pressure,
- Measuring equipment.

Detailed model of the developed brake noise dynamometer with measuring equipment is designed in software CATIA. Based on the 3D model, the technical documentation needed for building these technical solutions is made. Schematic view of measuring installations designed for testing the high-frequency disc brake noise is shown in Figure 9.

3.2 *Test bench with electric motor and disc*

Electric motor is manufactured by "SEVER" Subotica with nominal power of 4 kW at 2830 rpm. Torque on the drive shaft at the measuring point, including a dynamic component, must not be greater than the measuring range of torque sensor. The rotational speed of the drive shaft, *n,* is continually variable in range from 600 up to 3000 rpm with the stability $\Delta n < \pm$ 2% at the prescribed regime, with a maximum discrepancy δ_{max} = 1/30.

The electric motor is mounted stiffly on the base plate. The drive unit consists of: asynchronous electric motor fed by the frequency regulator (1), belt pulley transmission with ratio 1 (2), flywheel (3), disc brakes (4) (Figure 10). Rotation speed sensor (5) is mounted on the free end of the electric motor's shaft.

Flywheel on the input shaft is the disc with diameter *R*=0.35 m, a width of 0.045 m and mass 35 kg. Flywheel has the moment of inertia of 0.54 kgm^2 and it is corresponding to kinetic energy of the test vehicle, at low initial velocities, which are critical in terms of appearance of brake squeal.

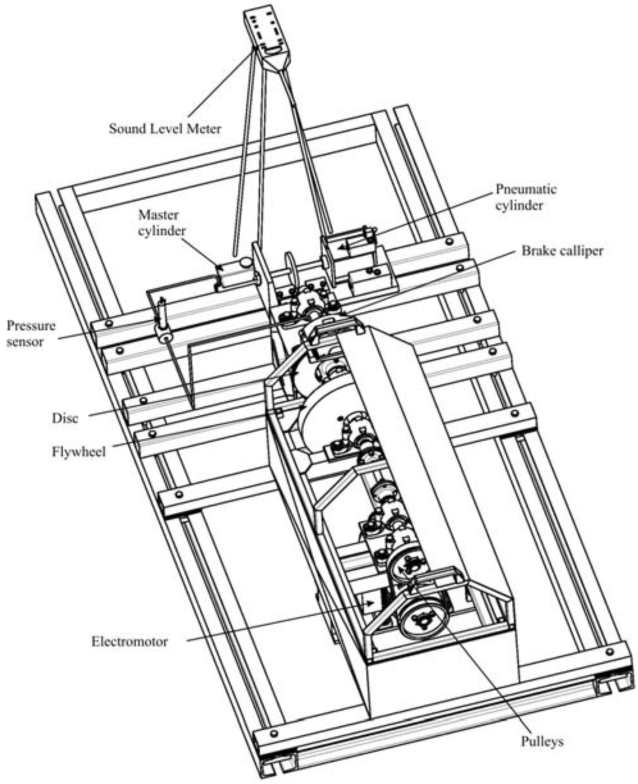
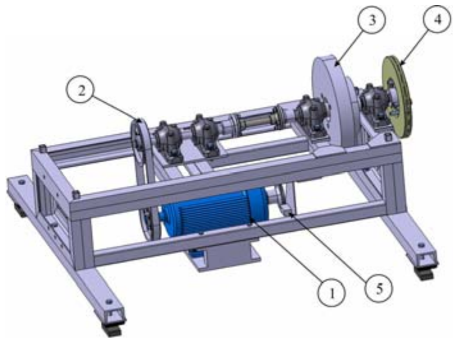


Figure 9: *Schematic view of laboratory installations designed for testing high-frequency noise of disc brakes*



1 – *Asynchronous electromotor* 2 –*Friction Drive Pulley*
3 – *Flywheel* 4 – *Disc brake*
5 – *Rotational speed sensor*

Figure 10: *3D model of the drive block of designed dynamometer*

3.3 *Measuring block*

The components of the measuring block formed to record the activation pressure in the cylinder of disc brake, *p*, brake torque, M_k, RPM of disc brakes, *n*, and the sound pressure level, *SPL*, as well as the connections of individual components are shown in photography in Figure 11 and the block diagram in Figure 12.

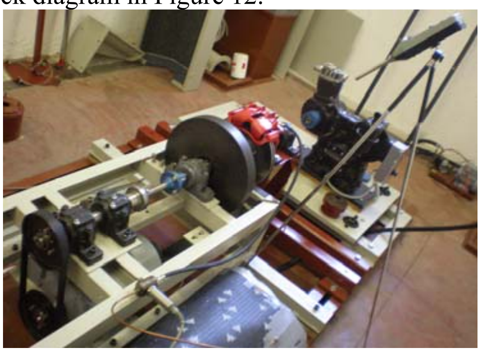


Figure 11: *Photo of laboratory installations designed for the brake noise investigation*

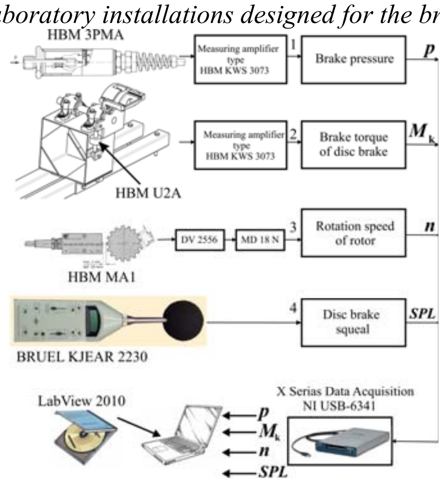


Figure 12: *The block diagram of measuring installation for disc brake noise investigation*

4. DISC BRAKE NOISE PROCEDURES

Basically, each vehicle manufacturer as well as each full brake system supplier has his own dynamometer test procedures and the standardization is quite poor. Today, two procedures are widely used and commonly accepted - the AK master (SAE J2522) for performance tests and the SAE J2521 [5], which was derived from it, for noise purposes. The SAE J2521 consists of an initial conditioning module after which the evaluation section is repeated three times with an optional fade and recovery module at the end. The evaluation module contains drag and stop brake applications as well as drag brake applications in forward and reverse vehicle direction. Nevertheless, an integral part of the release procedure of a new brake system is vehicle testing in Los Angeles (LACT) for US vehicles and in Mojacar for European vehicles.

One weakness that has been observed in the SAE J2521 procedure is the lack of a specification for environmental controls. A good example is the "morning sickness" problem. To replicate this kind of noise, J2521 would have to specify testing near 90% relative humidity and near freezing temperatures. It is anticipated that this may be one of the next steps in enhancing the capabilities of this matrix to screen for noise propensity. Summary of SAE J2521 procedure is shown in Figure 13.

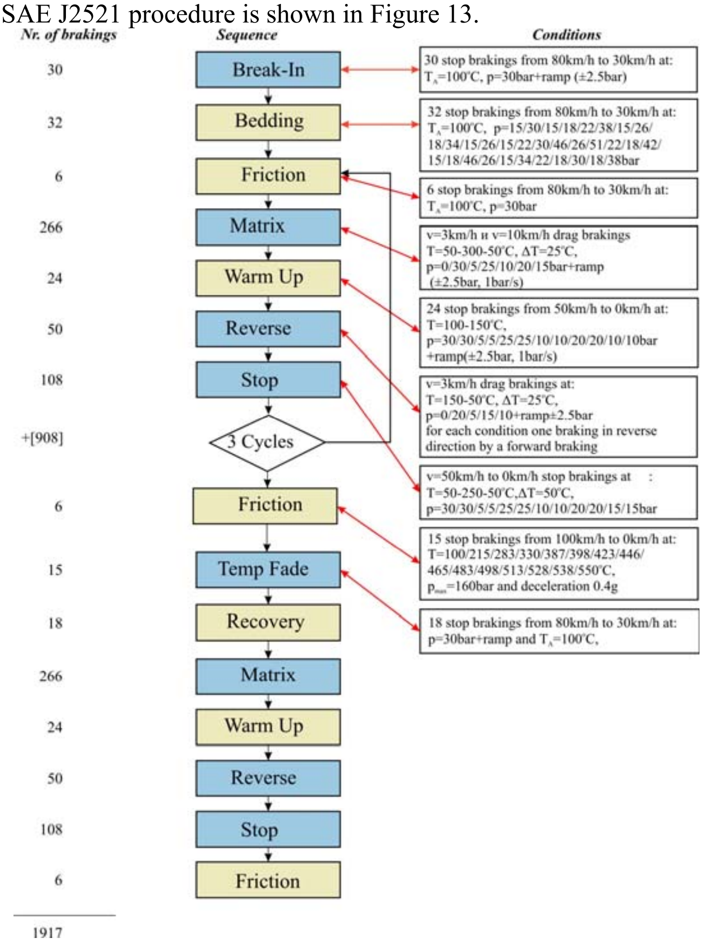


Figure 13: *SAE J2521 flow chart of the procedure [13]*

In the United States, the Los Angeles City Traffic (LACT) test is often used as the final evaluation of brake noise performance in vehicle development programs. This test on the streets of Los Angeles represents severe test conditions in an urban environment and is well known to generate significant brake squeal in susceptible vehicles. The advantage of this test procedure is that it has been shown to be effective in generating brake noise. The disadvantage is that it requires a vehicle and 2-3 weeks to run. It is difficult to incorporate such a lengthy test in the braking system development process.

The SAE J2521 procedure does not attempt to provide a substitute for the LACT test. Correlating a dynamometer test to a vehicle evaluation is difficult. There may be many differences in the components used in the two tests; tolerances and other variations may also have a substantial effect. Instead, SAE J2521 provides a fast process to screen for brake noise. Generally, without the optional fade-and-recovery section, J2521 can be carried out in 24-33 h on a modern chassis dynamometer. Many researchers go by the "rule of thumb" that the J2521 test is more severe than LACT. In other words, the J2521 matrix may detect the noise that does not appear during vehicle testing. Experience has shown that it is not often that a noise is found in LACT testing that is not seen on J2521 tests.

Although dynamometers have been used for brake noise evaluation for decades, the first internationally recognized standard was SAE J2521, published in June 2001. Therefore, this is a well-established area of testing with a relatively new standard for measurement procedure. There is still much to be learned and improved.

It is anticipated that there will be further refinements to dynamometer test procedures to improve their ability to screen for squeals found in actual vehicle operation. Some potential areas for improvements include:

- Establishing requirements for tests as well-defined environmental conditions,
- Refining the balance between the various matrix segments such as drags, decelerating stops, backward/forward sections, etc.
- Including modified burnish cycles for different types of friction materials or different applications.

SAE J2521 procedure proved to be a good tool for screening for the propensity of a brake to generate squeal. However, there is a need for further improvements, including the addition of environmental conditions. Experience has also shown that dynamometer testing does not correlate directly with LACT test results. The question to be addressed for the future is whether it is necessary and possible for a dynamometer-based screening procedure to match this particular vehicle procedure [5].

It is expected that dynamometer tests eventually become a better screening tools than LACT in that they will more accurately predict squeal, require less test time, and allows faster change-over. The dynamometer test will, however, be part of the development process, and not a final check of the braking performance.

4.1 *AK Noise Procedure*

The AK noise test procedure was developed by a working group in Germany that included automobile, brake systems and friction materials manufacturers. The fundamental concept consists of a matrix of tests that allows one to screen a braking system for its propensity to generate squeal. The AK noise procedure begins with a burnish phase in which new friction couple is permitted to accommodate itself. This is followed by a conditioning step. The essence of the noise monitoring is found in the next segment - city/country. Tests are run using two test speeds, 3 and 10 km/h. These low speeds are used because this is frequently where noise occurs. These are drag tests. The speed is held constant while a specified brake pressure is applied. A wide range of temperatures from 50 to 300 °C is utilized in this evaluation. During these tests, the pressure is variable instead of holding applied pressure at a constant value. The pressure is increased linearly from a value less than the normal value to a value greater than the nominal value and returned to the starting point. The triangular profile assures that if there is an applied pressure that is different from the nominal value at which noise occurs, this phenomenon is not missed.

After a conditioning segment, forward-and-reverse procedure is run. The concept behind this segment is to record the noise occurring when the vehicle is operating in the reverse direction. Testing is run at 3 km/h. It is not uncommon for a customer to complain about a squeal that occurs only when backing from a parking place.

Along with the city/country and conditioning segment, this component is repeated twice after the first run-through. The result is 990 stops total. Next, there is a short segment of deceleration stops. These stops are from initial velocity of 30 km/h to complete stop. Again, a range of temperatures and pressures are evaluated. A total of 54 stops is performed. The high heat conditioning section employs a brief series of high-temperature stops. This segment is taken from the AK master procedure. The city/country segment is then run again after the high-temperature segment. A key reason for this segment is to screen a greater propensity for noise after a high-temperature cycle. The forward/reverse segment is also repeated to evaluate the change in noise performance due to high-temperature cycling.

There are many ways to present the data from the AK noise test. One typical way is to plot the occurrence of noise. The number of noise occurrences can be recorded or, more frequently, the percentage of stops (or brake applies) in which the noise occurs is recorded. Generally, low percentages indicate good noise performance, while high percentages indicate poor noise performance. Every auto manufacturer and each supplier have algorithms for defining what acceptable level of noise is. Most would consider percentage below 1 as very good performance.

It must be noted that AK noise test method is not a published standard, but a standard prepared by a group in Germany with some restrictions on its distribution. Many versions of this procedure have been developed, in part because it is seen by some as proprietary. One of the cited limitations for this procedure has been that this does not incorporate enough deceleration sequences. Much of this procedure is focused on contact speed drags [1].

4.2 *The developed test procedure for screening high-frequency disc brake squeal*

The developed test procedure includes two categories of tests: braking with a constant rotation speed of the disc and different braking pressure and braking with a constant pressure and at different speeds. Tests that have been carried out correspond to braking with clutch-off *i.e.* with interrupted power transmission.

Test Modes:
Constant rotation speed of disc and different brake pressures:

- Constant speed in range from 250 to 1000 rpm.
- For every rotation speed, different pressures from 0.5 to 3 MPa with pressure increment Δp=0.5 MPa is applied.

Constant brake pressure and different rotation speed of the disc:

- Constant pressure in range from 0.5 to 3 MPa.
- For every pressure, different rotation sped from 250 to 1000 rpm with step Δn=50 rpm is applied.

In some braking regime (e.g. low brake pressure and high initial engine speed) there is only partial braking *i.e.* partial declining of disc's speed from the initial speed of v_1 to end speed of v_2 , while in other cases, it was braking until stopping of the disc brake.

Temperature measurement:

- Temperature was measured by a laser thermometer, Minolta, type Minolta-Land Cyclops Mini Laser for non-contact measurement of surface temperature. Thermometer has a platinum probe; temperature measurement range is from -50 ºC to 500 ºC, with accuracy of 1% of the measured value,
- Temperatures were measured at the midpoint of the brake disc.

It was important to make this temperature measurement in order to avoid overheating. If the system is cold, the working temperature should be raised up to 80 - 90 °C. This is achieved by braking with low pressure with engaged electric motor.

Measuring signals from all sensors are then led to National Instruments NI USB-type-6341 data acquisition system (Figure 14) which in interface with LabVIEW 2010 software, collects, analyzes and represents in real-time and stores the measurement results.

Figure 14: *National Instruments NI USB-type-6341 data acquisition system [14]*

During experimental research measuring value with the maximum change rate in time is the sound pressure level so its characteristic sets sampling speed. An examined high-frequency disc brake squeal has a maximum expected frequency of 20 kHz because it is the human audible range limit [15]. According to Nyquist-Shannon sampling theorem [16, 17] it is required that the sampling frequency must be at least twice higher than the frequency of the signal that we want to transfer to digital form, otherwise aliasing effect occurs. Therefore, the selected sample frequency was 50 kHz. So the data sampling period was $2 \cdot 10^{-5}$ s.

Selected time period of signal recording was 5 s, and this is, with respect that the duration of the braking process is maximum 1 s, a sufficient period to capture the processes before and after the brake (the level of environmental noise, influence of the drive unit noise, the effect of residual braking to stopping time of the disc).

The characteristics of the data collection process during the performed tests are shown in Table 2.

Table 1: *The characteristics of the data collection process*

Sampling period	Δt	$2\cdot10^{-5}$ s
Measuring time	T	5 s
The frequency band of signals	f_g	0 до 20 kHz
The minimum sampling rate	$f_{min}=2f_g$	40 kHz
The sampling frequency	$f_{max} = f_o = \frac{1}{\Delta t}$	50 kHz
The number of samples in one measurement	N	250 000
Number of repeated measurements	n	3
Measurement Error	$\sqrt{\frac{2}{N}}$	0,0028

CONCLUSIONS

Even today, if a significant number of vehicle tests is needed to be performed for final verification of the brake design, dynamometer tests are used early in the development stage, when representative vehicles are not available or during problem resolution stages, when a better controlled design of experiment is needed. Inertia dynamometers are used to test the single brake assembly up to the whole mechanical brake system, often also including suspension. Dynamometers are used in different operational modes. During a test procedure, the time between the brake applications is either firmly specified (time controlled mode) or the next brake application is started when a specific (e. g. disc) temperature is reached (temperature controlled mode), independent of the cooling time in the latter case. For special test procedures, the control parameter during a brake application is either brake line pressure (pressure controlled) or the brake torque (torque controlled), besides the initial and final velocity and in the case of temperature control also initial temperature.

The objective of this paper is to develop original methodology for investigation the mechanism of high-frequency oscillations of a disk brake system that manifest themselves as squealing sound and their effect on indicators of braking efficiency and the overall vehicle noise levels. Comprehension of this phenomenon and elimination of the adverse effects is a priority in today's development and refinement of motor vehicle brakes. This goal is achieved by development and implementation of an experimental system for testing the brakes that can also verify the simulation results.

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