ANALYSIS OF INTERIOR NOISE IN SPECIAL PURPOSE VEHICLES

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Abstract: *As vehicles have evolved from simple to complex machines with specific configurations depending on their main role, the issue of interior noise has become a topic of interest. The present paper presents a model of experimental acoustic determinations made based on standardized acoustic emission factors for a vehicle in the N2G category, taking into account the volume of the vehicle, its speed, road configuration, and the distance from the receiver. Thus, significant conclusions are reached regarding the level of acoustic emissions in the vehicle cabin. Cumulative preliminary estimates were also made for the level of interior noise in the special purpose vehicle, monitored while stationary and in motion, in order to obtain an initial picture of the cumulative impact of noise and vibrations generated by acoustic sources originating from the operation of the vehicle. Noise tests were performed under realistic operating conditions during the intensive testing period.*

Keywords: *Noise level, acoustic emission, noise test, experimental determinations, vehicle cabin, interior noise.*

1. INTRODUCTION

The upward development trend of technology and a the sudden increase in market competition within the civil and military automotive industry and the current political-military context, dictates manufacturers' obligations to fulfill the increasingly complex requirements of the user in terms of economy, comfort, ergonomics safety and environmental protection. All from above have influenced car manufacturers and the automotive industry to pay attention to technical innovations to meet the requirements related to increased cabin comfort, vehicle safety, and researchers to bring the innovation to the field [1].

The noise, vibration and harshness (NVH) of a car is among the issues of interest in the automotive industry since the decade passed [2]. Because noise crucially affects the level of passenger comfort, one of the specifications for a good quality car is one that has low interior noise level in addition to conventional features such as car performance when it comes to civilian vehicles. This becomes all the more difficult as the modern car becomes quieter; therefore, the driver's sensitivity to noise increases [3].

Regarding vehicles with special purposes, such as those used by the military, the issue of interior noise is studied from the perspective of the harmful implications on the health of the passengers. In this sense, noise becomes the source of producing a series of health problems, such as: communication and concentration difficulties; stress and irritability; sleep disorders; cardiovascular problems and negative effects on the endocrine system, on performance and work capacity that lead to a global decrease in the level of performance in activities. Also, a noise level between 35-70 dB, for a long time, to which the driver of a special purpose vehicle can be subjected leads to the appearance of fatigue, weakening of vision, difficulty in understanding speech and even causing headaches for a noise level which exceeds the value of 70 dB (such a high sound level can occur, for example, when traveling at a high speed of over 90 km/h on the highway) [4]. The harmful character of noises is amplified if they are accompanied by vibrations, just as the harmfulness of vibrations increases when they are accompanied by noises [5, 6].

The special purpose vehicles have different configurations depending on the destination, the structure of the vehicle being adjusted according to mobility criteria, specific reconnaissance activities (off-road vehicles), with or without ballistic properties, with different crew arrangements depending on the activities carried out (in the compartment, in the turret, for vehicles equipped with a turret, in the trunk). In addition to the fact that these vehicles must be equipped with additional systems to ensure the safety of passengers, they must also include ergonomic properties of the vehicle. Ergonomic properties include the ability to adjusting the interior of the vehicle to the characteristics of each individual drivers and crew members. Vehicle structure should be adapted to most users and allow individual adjustments, taking this into account dimensions, in order to: better visibility from vehicle, higher comfort, comfortable seat, lighter better driving, access and use of controls and devices, better sound and heat insulation, reduced vibration effect and driver fatigue.

Off-road vehicles include special engine vehicles that are part of the N2G category, classified in accordance with RNTR 2, special purpose vehicles that are used both on regular roads, in normal weather conditions and on difficult terrain and in complex weather conditions, for specific activities, usually used by the military. For these reasons, especially due to their use in complex weather missions and activities and difficult conditions, it is necessary that manufacturers and researchers who develop and bring improvement concepts on these kinds of vehicles, pay special attention to testing and adjustment models to comply with the standards existing during design and development of test models, in view ensure that the user's health is protected [7,8].

A problem specific related to special purpose off-road vehicles regarding the consideration of the previously listed requirements comes from the fact that they have a long life span, which can causes them to lag behind automotive industry standards which are constantly changing [9].

Thus, the present paper presents a strategy for monitoring and measuring as well as obtaining important data regarding the acoustics of the passenger compartment of special purpose vehicles, with the aim of outlining new research directions for the selection of the best available techniques, with the aim of making contributions for the additional mitigation of the impact potential noise on the passengers, as well as the implementation of a strategy that leads to the improvement of the interior acoustic comfort level.

2. THE PERCEPTION OF NOISE BY THE HUMAN AUDITORY SYSTEM

The main human auditory organ, specialized in the transformation of sound signals and noise, in general, into auditory sensations, is the ear.

The human ear, divided into the external ear, the middle ear and the inner ear, has the role of transforming the pressure variations that accompany a sound wave into electrical signals, which are finally transformed in the cortex into auditory sensations.

The human auditory system has the ability to do, in this process of transforming an air pressure variation into sensation, several analysis processes, an analysis in frequency, distinguishing different frequency sounds, an analysis in intensity, which refers to the fact that it distinguishes the different amplitude of two sounds of the same frequency, and can also amplify or attenuate perceived sounds that lie in different frequency bands. We can also talk about the situation where a sound with a certain level of sound intensity can mask another sound with a lower intensity. The mechanisms underlying the creation of an auditory sensation are extremely complex, hearing essentially having a valid general character, but also a certain particular character [10,11].

About the human ear it can be said that it perceives sounds that are located in a wide frequency band, more precisely from 16 Hz - 16000 Hz. Below and beyond these limits, the human being has no auditory sensation. With age, the sensitivity of the human auditory organ decreases. Any physiological or traumatic condition of it can lead to hearing impairment or even deafness. Also, prolonged exposure to noises with high acoustic levels inevitably lead to hearing loss, which can have different degrees [12].

The frequency analysis of sounds takes place in the inner ear, where the muscle bundles of the basilar membrane behave like the strings of a piano, being excited by different frequencies [13].

The threshold of audibility is the minimum at which the human ear perceives a sound, the level at which a person has auditory sensation. This threshold depends on the frequency of the emitted sounds, for example at the frequency of 1 kHz, the threshold value is 2 dB, between 2000-6000 Hz due to the amplifications in the ear, the perception drops below this level, appearing a level that shows that the auditory sensation is excited by variations of the pressure below the reference value p=20µPa [14].

The audibility range is limited in terms of the level of two curves, the audibility threshold curve p_A and the pain threshold curve p_D, and in terms of the band frequency range 16 Hz-16 kHz. For a normal ontological listener, the pain threshold shows an approximately constant plateau, with a higher sensitivity of the ear in the amplification zone 2000-6000 Hz. The pain threshold located in the area of a level of 120 dB, shows that the sensitivity area, under normal conditions, of the auditory apparatus extends over an extremely large beach, from 20 µPa to 20 Pa. Although in relation to the atmospheric pressure p_{atm} =100 kPa, the pressure value corresponding to the pain threshold pressure seems small, it is a pressure variation, a dynamic quantity. The forces that act on the sensitive mechanisms of the middle ear are very small, if we refer to the area of the eardrum which is about 1 cm^2, it supports in the area of the pain threshold 0.02 N and a force a million times smaller, the case of the threshold of audibility [15].

The different perception of sounds by the human ear compared to measuring devices required the creation of different scales for measuring the acoustic pressure level depending on the field in which they are used, present in the specialized literature. The adaptation of the measurement system, by which real values are obtained by objectively measuring the sound pressure level, according to the auditory sensation of the listener, led to the introduction of corrections by means of standardized weighting scales with the designations A, B, C and D, which to take into account the criteria established after the experiments. A weighting scale is a set of numerical values by which the objective sound pressure level measured at different frequencies is corrected.

Since, at low frequencies < 200 Hz the sounds are poorly perceived, the corrections are negative, and in the range 2000-6000 Hz, where the sensitivity of the ear is maximum, the corrections are positive [16]:

- The A scale is the one that comes closest to human auditory perception and includes significantly higher corrections for the low frequency spectrum, for normal sound intensity levels, <60 dB.

- The B scale, follows the subjective perception of the human ear, for moderate levels of the acoustic intensity level, > 60 dB, for which the sensitivity of the human ear flattens.

- The C scale is the scale that comes closest to the measured sound intensity level, introducing corrections only if the noises are very loud.

- The D scale is studied for the study of aircraft noise and introduces significant corrections in the frequency band where the ear's sensitivity is maximum 2000-6000 dB

The corrections that are introduced in the weighted scales lead to an overall decrease in the sound level, compared to the actual, measured sound level. That is why when acoustic level values are presented, the scale in which they were weighted must also be specified [17].

3. DETERMINING THE NOISE LEVEL INSIDE SPECIAL PURPOSE VEHICLES

3.1 Technical generalities regarding the tested vehicle

In this study, data obtained based on experimental determinations on off-road special purpose vehicles are presented, one of which is the Panhard vehicle. Tests were carried out on vehicles of configurations in this category, creating a database, which will later be interpreted, presenting significant conclusions from a scientific point of view.

One of the tested models, for which the obtained values are of interest from the point of view of the noise issue, is presented in Fig.1 a) and b), while Table 1 presents general technical information about this off-road vehicle.

Table 1

General information	Model Panhard
Type	Off road
Category	N2G special vehicle
Mass of the vehicle	5050 kg
Drive	4x4
Pneumatics	255/100R16 126K
Speed	3500 rpm
Nominal engine power	122 KW
Seats	4

(a)

(b)

FIG. 1 The vehicle subject to experimental determinations

3.2 Experimental testing methodology

The noise produced in the passenger compartment of the special vehicle types analyzed is measured with the vehicle in motion and with the vehicle stationary, in accordance with ISO 5128: 1980 on the measurement of noise inside motor vehicles. In the case of a hybrid electric vehicle whose internal combustion engine cannot operate when the vehicle is stationary, the emitted noise level shall only be measured in motion.

The equipment used to measure the sound level is a precision sound level meter or an equivalent measuring system meeting the requirements for instrument class 1 (including the wind shield recommended by the manufacturer, if applicable). These requirements are described in the International Electrotechnical Commission (IEC) standard "IEC 61672-1:2002: Precision sound level meters", second edition. Measurements are made using the "quick" response of the acoustic measuring instrument and the "A" weighting curve also described in "IEC 61672-1:2002". If a system is used that includes periodic A-weighted sound pressure level monitoring, readings shall be taken at time intervals of no more than 30 ms (milliseconds). For the cases studied, intervals of 60 s were taken into account.

Before carrying out the experimental determinations for the passenger compartment of special purpose vehicles, an analysis of the research in the field was necessary: articles, books and various other publications and not least of some international standards that refer to the acoustics of the vehicle passenger compartment. Based on the exploratory approach regarding the bibliography of the study, a gap was identified regarding the documentation made by researchers and specialists in acoustics and vibrations in our country [18-20]. Thus, the research methodology is carried out according to the block diagrams in the Fig.2, taking into account compliance with the standards of acoustic determinations in force.

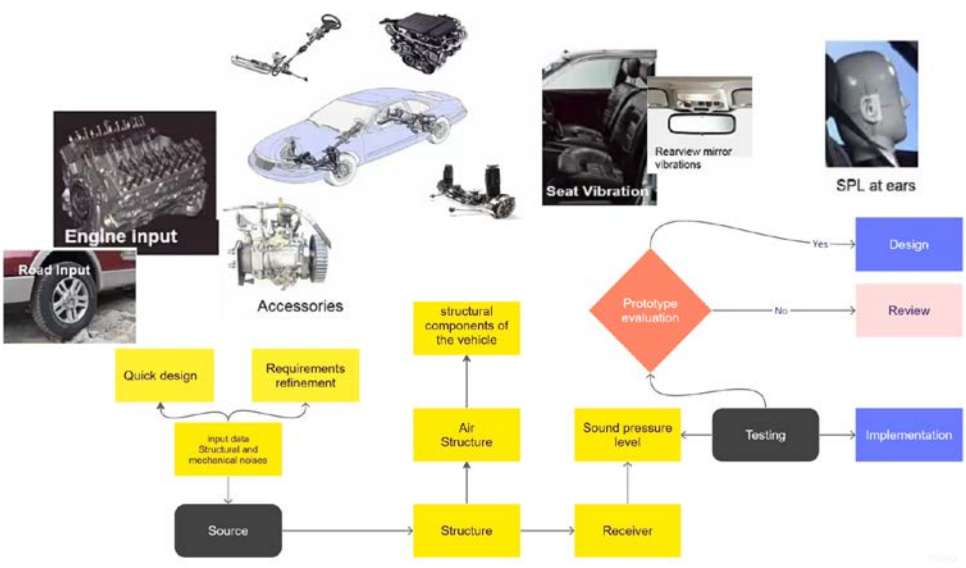

FIG. 2 Block diagram of the noise analysis in the vehicle cabin.

In the block figure related to the research methodology, the input data and the output data of the complex dynamic system are represented, regarding the problem of interior noise in vehicles. The noise from prominent noise sources as a result of the operation of the vehicle propagates in its structure. Also as a result of exploitation, another prominent source of noise comes from the interaction of the vehicle with the external environment (air) as well as structural noise. At the receiver, a sound is perceived as acoustic pressure. Based on the experimental determinations, the equivalent acoustic pressure values were determined. As a result of the results obtained, a prototype is evaluated or improved to fit the acoustic norms recommended by the standards.

The realization of some improvements regarding the acoustics of the interior of the vehicles is based on an integrated system: spectral analysis of the noise produced inside the vehicles, creation and management of the research input database, virtual modeling based on advanced mathematical algorithms, numerical testing of the effectiveness of noise mitigation, feedback system of design, model making, testing and verification, testing and verification in real conditions, achieving the improvement of the NVH properties of the vehicle interior.

The integrated system for the analysis of the interior acoustics of the vehicle is based on factors of a subjective nature (receiver) and of an objective nature (frequency analysis using specific acoustic descriptors or finite element analysis).

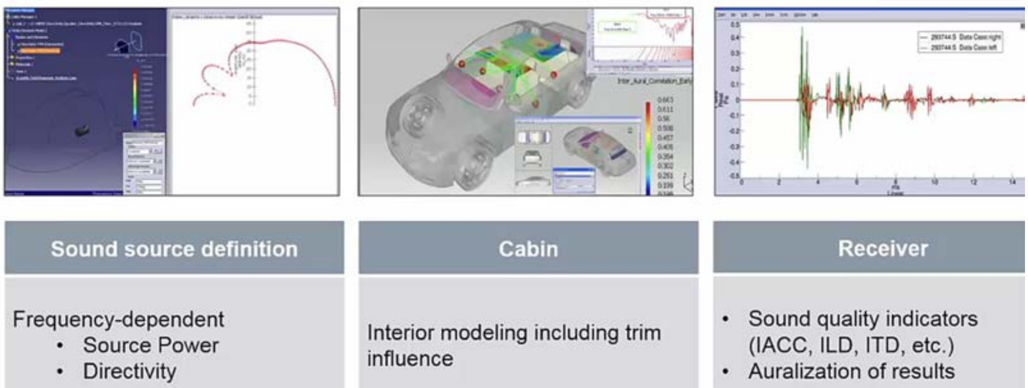

FIG. 3 Integrated system proposed for the interpretation of results

The testing methodology proposed for the experimental determination of the noise level in the cabin of special purpose vehicles is preceded by developed theoretical models: the finite element method and mathematical formulas. This is how the acoustic pressure level is determined inside special purpose vehicles, in the N2G category. This involves: preparation of the working environment, namely the track for making measurements, which is a straight asphalted ground for a length of 500 m, without being covered by snow, tall grass; in the immediate vicinity of the test track there are no obstacles at a distance of 20m (buildings, vehicles, large objects), which could influence the reflection of sound waves; a measuring device was further identified, meeting the requirements for class 1 instruments, weighted in frequency and time in the A scale, namely a sound level meter; the next step is to identify the environmental conditions with the anemometer, a temperature of 25 ^{0}C was identified in the reference range of +5 and +40 ^{0}C and a wind speed of 3m/s below the reference wave level of 5m/ s; also before and after each measurement the sound measuring device was calibrated and the background noise was measured in an interval of 10 seconds; finally, the measuring devices were positioned and the values of the interior acoustic pressure level were determined, for different engine operating speeds of special purpose vehicles.

The obtained data were processed and constituted in a database, which is analyzed later.

3.3 Determining the noise level inside special purpose vehicles

For each speed, 100 values of the equivalent continuous sound level were obtained, in an interval of 60 s. The measurements were performed on a test track characterized by terrain, without obstacles, these being located at a distance of at least 20 m from the test track.

a) Measurement method. The stages for the N2G category vehicle, Panhard type, are presented. The noise produced by the type of vehicle under measurement is measured with the vehicle stationary, for various engine operating speeds.

b) Equipment required for measurements. The following devices were used, necessary to perform the measurements: PC system (laptop); Sound analysis software; Sound level meter (SLM), accuracy class 1, with frequency and time weighting, according to the specifications of international standards such as IEC 61672 – 1, instrument (portable) which is designed to measure sound pressure levels in a standardized way. It responds to sound in roughly the same way as the human ear and provides objective, reproducible measurements of sound pressure levels. This sound level meter comprises a microphone, a preamplifier, signal processing and a display. The microphone converts the acoustic signal into an equivalent electrical signal. The most suitable type of microphone for sound level meters is the condenser microphone, which combines precision with stability and reliability. The electrical signal initially produced by the microphone being very low is then amplified by a preamplifier before entering the main processor. Signal processing includes frequency and time weighting as specified by international standards such as IEC 61672 – 1; Multimeter for measuring wind speed and air temperature with an accuracy of ±(0.1m/s+5% of the measured value - 0 to 2 m/s), ±(0.3m/s+5% of the measured value - 2 to 15 m/s).

c) Verification of compliance with the requirements. The conformity of the instruments for acoustic measurements is verified by the existence of a valid certificate of conformity. A certificate of conformity is considered valid if the certification of conformity with the standards has been carried out within the last 12 months for the sound calibration device and within the last 24 months for the measuring system. All compliance tests must be performed by a laboratory authorized to carry out calibrations corresponding to the specific standards in force.

d) Calibration of the entire acoustic measurement system for the series of measurements. At the beginning and at the end of each series of measurements, the entire acoustic measurement system shall be checked by means of an acoustic calibration device that complies with the requirements for acoustic calibration devices of accuracy class 1 according to standard IEC 60942:2003. Without any other adjustment, the difference between readings must be less than or equal to 0.5 dB. If this value is exceeded, the measurement results obtained at the last satisfactory previous check are not considered valid.

e) Measurement conditions. The surface of the test track and the dimensions of the test polygon comply with the ISO 10844:2011 standard. The range surface is not covered with loose snow, tall grass, lumps of dirt or ash. There must be no obstacle that can affect the sound field in the vicinity of the microphone and the sound source. The observer making the measurements must position himself so as not to affect the readings of the measuring instrument. Measurements are not made in adverse weather conditions. It must be ensured that the results are not affected by wind gusts. Meteorological measuring instruments must be positioned in close proximity to the test area at a height of 1.2 m ± 0.02 m. The measurements are carried out when the ambient air temperature is between + 5 °C and + 40 °C. No tests shall be performed if, when measuring noise, the wind speed, including gusts, at the height of the microphone exceeds 5 m/s. During the noise measurement period, representative values for temperature, wind speed and direction, relative humidity and barometric pressure are recorded. Any peak noise value that appears to be unrelated to the overall sound level characteristics of the vehicle is ignored in the reading. The background noise shall be measured over a 10-second interval immediately before and immediately after a series of vehicle tests. The measurements are carried out with the same microphones placed in the same positions as during the test. The maximum A-weighted sound pressure level is recorded. The position of the sound level meter has a coordinate in the horizontal plane of 0.7±0.04 m, and in the vertical plane 0.2±0.02 m, as in the Fig. 4. These reference coordinates are measured according to the plane of symmetry, in the vertical plane of the driver's seat. The position of the microphone must be in a horizontal plane, mounted so that it is not influenced by the vibrations of the vehicle. Before starting the measurements, bring the engine to normal operating conditions.

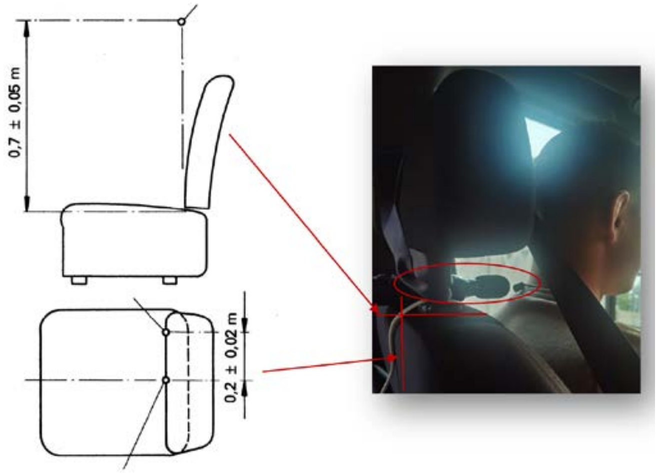

FIG. 4 Position of microphones for indoor noise determination according to ISO 5128:1980.

f) Noise measurement in the passenger compartment of the special purpose vehicle. The noise level measurement is carried out at a standstill with the engine running. Measurements are taken without any trailer.

g) Vehicle category: N2G, special purpose vehicle.

h) Work method and results obtained. As a result of the experimental determinations, the following values of the internal noise level were obtained while stationary for different operating speeds of the engine:

- **Speed of n=800 rpm:**

Table 1. Synthesis of sound level values, obtained over 60s, at n=800 rpm of the engine (at idle), stationary

n[rot/min]	800	800	800	800	800	800	800	800	800
Leq [dBA]	56.4	58.0	57.1	57.9	56.9	57.4	57.6	56.6	57.1
n[rot/min]	800	800	800	800	800	800	800	800	800
Leq [dBA]	56.8	57.1	56.7	57.1	57.4	56.7	57.5	57.5	57.1

The average value for the noise level at n=800 rpm is: 57.78 dB(A).

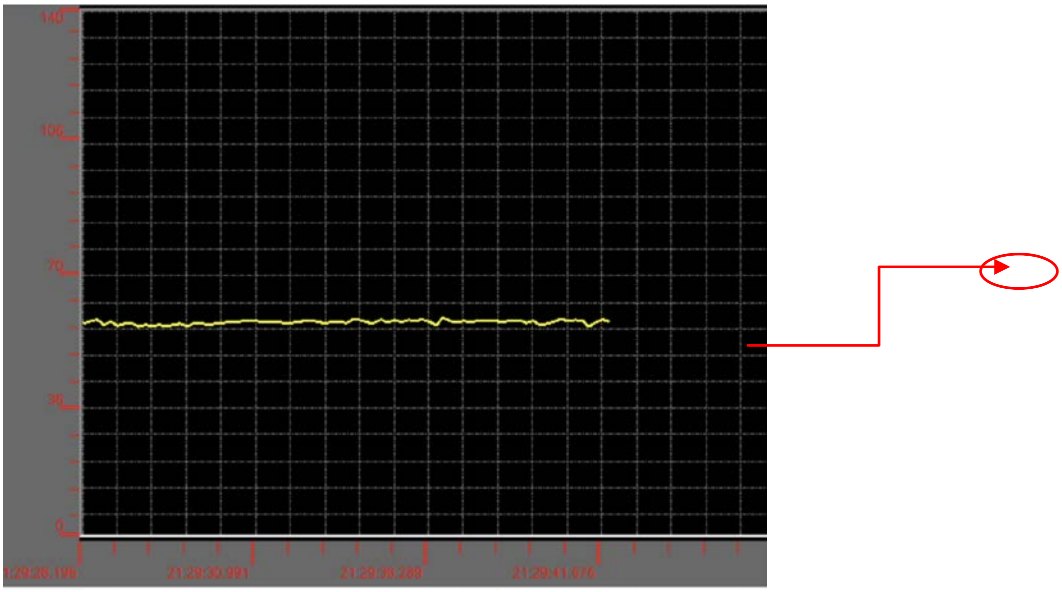

FIG. 5 Time dependence graphs of interior noise levels, for one combat all-terrain vehicle, at n=800 rpm, stationary

- **Speed of n=1500 rpm:**

Table 1. Synthesis of sound level values, obtained over 60s, at n=1500 rpm of the engine (at idle), stationary

n[rot/min]	1500	1500	1500	1500	1500	1500	1500	1500	1500
Leq [dBA]	67.4	69.3	67.7	68.7	69.1	67.3	68.3	67.5	69.7
n[rot/min]	1500	1500	1500	1500	1500	1500	1500	1500	1500
Leq [dBA]	69.9	68.5	68.8	68.8	69.4	68.3	67.5	69.7	69.9

The average value for the noise level at n=1500 rpm is: 69.3 dB(A).

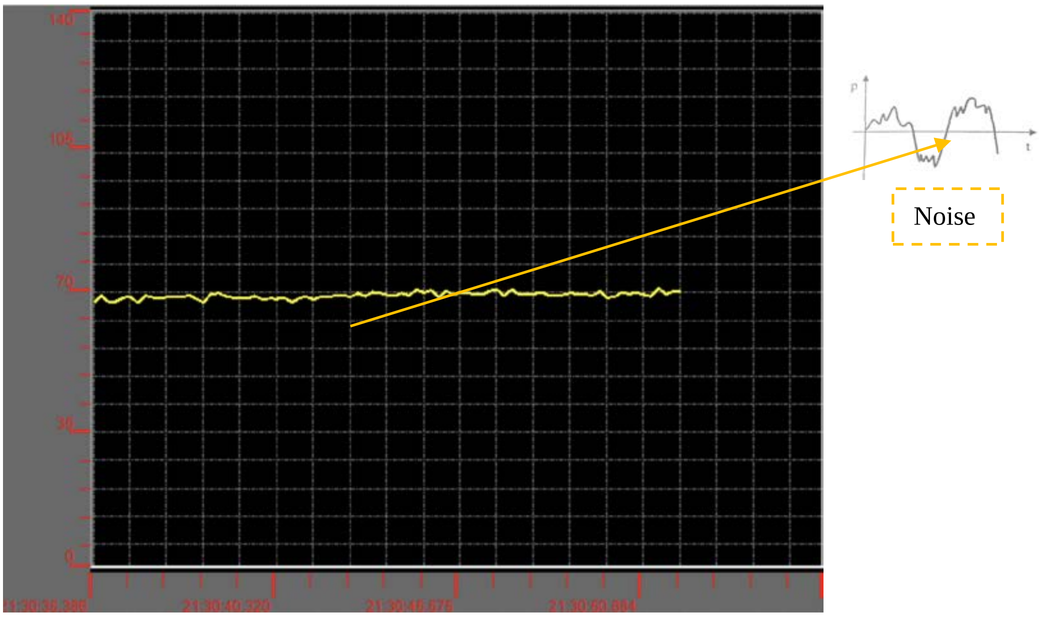

FIG. 5 Time dependence graphs of interior noise levels, for one combat all-terrain vehicle, at n=1500 rpm, stationary

- **Speed of n=2000 rpm:**

Table 1. Synthesis of sound level values, obtained over 60s, at n=1500 rpm of the engine (at idle), stationary

n[rot/min]	2000	2000	2000	2000	2000	2000	2000	2000	2000
Leq [dBA]	71.8	78.4	78.2	72.1	72.5	71.0	71.5	70.5	71.4
n[rot/min]	2000	2000	2000	2000	2000	2000	2000	2000	2000
Leq [dBA]	71.3	71.9	71.8	71.9	71.9	72.0	74.0	75.0	74.6

The average value for the noise level at n=2000 rpm is: 74.44 dB(A).

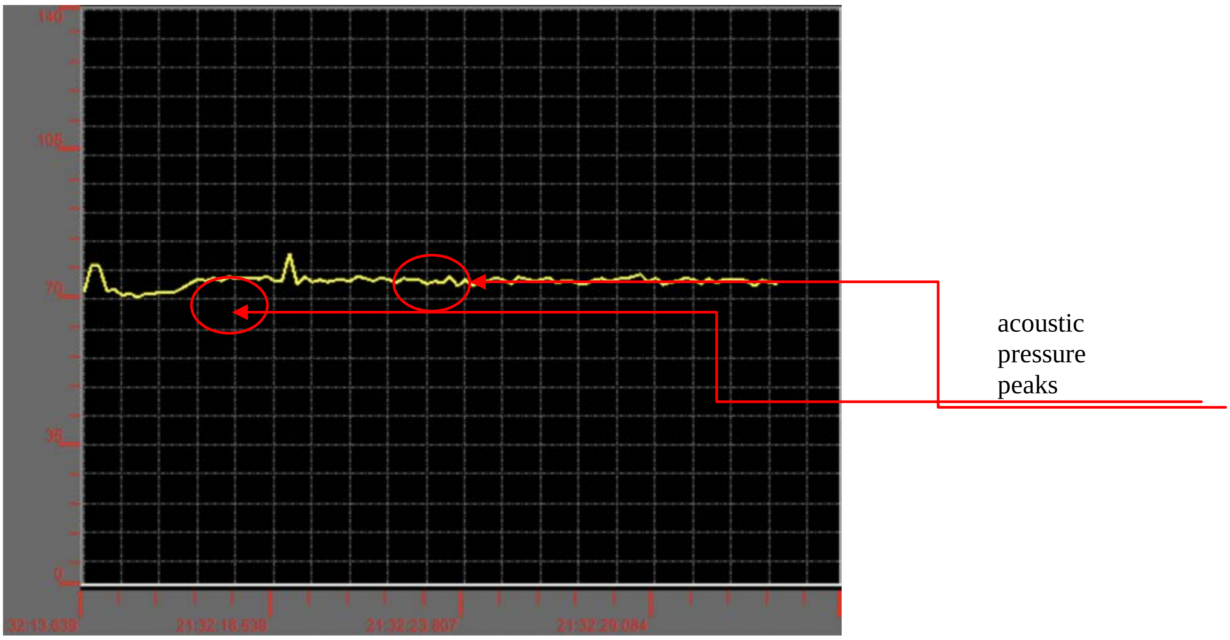

FIG. 6 Time dependence graphs of interior noise levels, for one combat all-terrain vehicle, at n=2000 rpm, stationary

NOTE: For each speed, 100 values of the equivalent continuous sound level were obtained, in an interval of 60 s. The measurements were performed on a test track characterized by terrain, without obstacles, these being located at a distance of at least 20 m from the test track.

4. INTERPRETATION OF EXPERIMENTAL RESULTS

Analyzing the results obtained from the experimental determinations, the dependence graph of the internal acoustic pressure level can be drawn according to the speed.

A comparative analysis is also carried out between a regular off-road configuration vehicle subject to the same test methodology and the special purpose vehicle, based on the values obtained.

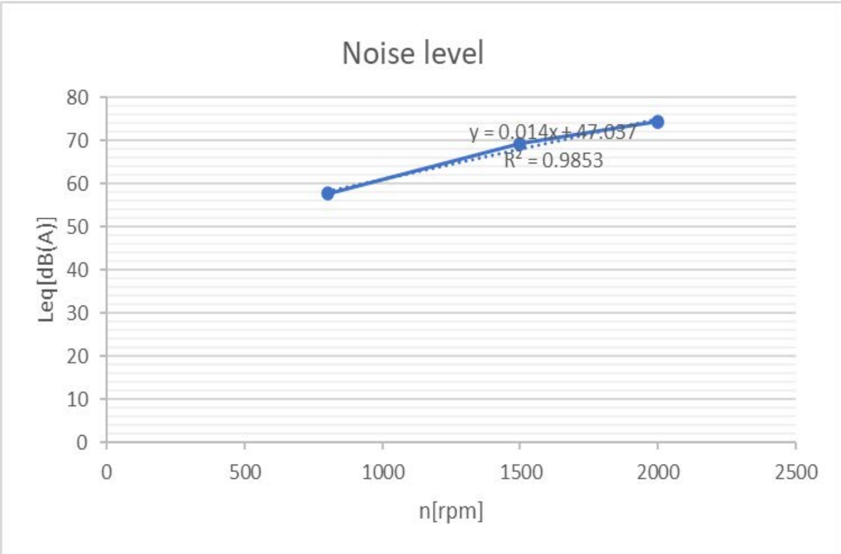

FIG. 7 Dependence graphs of interior noise levels, for the tested combat all-terrain vehicle.

The acoustic pressure values increase from the average value of 57.78 dB(A), at the speed of n=800 rpm, to 69.3 dB(A) at the speed of n=1500 rpm, up to 74.44 at n=2000 rpm min. It is also found that there are pressure peaks that reach up to 78.4 dB(A). The dependent equation for the definition of the average values of the three average values for the revolutions: 600 rpm, 1500 rpm and 2000 rpm is: y=0.014x+47.037.

Analyzing the graph drawn in **fig. 7**, it can be stated that the values of the internal acoustic pressure level obtained while stationary, increase significantly with the motor speed.

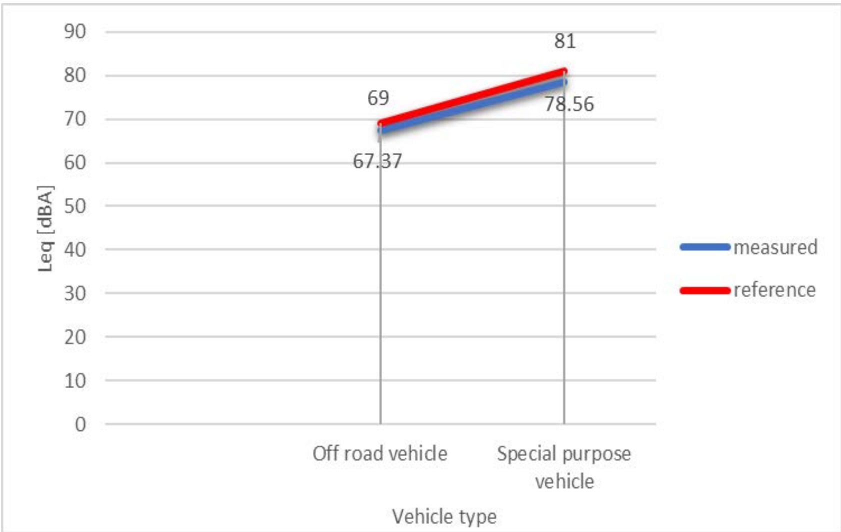

FIG. 8 Dependence graphs of interior noise level, for the combat all-terrain vehicle and off road vehicles. Comparison.

According to the graph drawn in Fig.8, based on the measurements performed on an off-road vehicle and a special purpose vehicle, it can be seen that the values of the acoustic pressure level in the passenger compartment are located below the reference line of the values allowed by the standard, but they are close in values, the difference being only 2 dB-3dB. The graph represents the average values of Leq at 2500 rpm. Special purpose vehicles show values of more than 10 bB, stationary compared to regular off-road vehicles. This fact implies equipping them with anti-noise headphones, as well as taking additional measures to reduce the noise so that it is not harmful to the passengers.

CONCLUSIONS

Synthesizing the predictive theoretical studies through calculation methods as well as the analyzed experimental results, the following conclusions are presented:

- For the off-road vehicle of the N2G special vehicle category, the sound pressure level in the passenger compartment, when stationary, can reach up to 74.44 dB.
- Based on the experimental determinations, it was found that there are pressure peaks that reach values of up to 78.2 dBA, or even values of 78.4 dBA. High indoor sound pressure values even for a short time affect passengers in a negative way.
- According to the experimental determinations of noise inside special purpose vehicles, an average interior acoustic pressure value of 57.78 dB(A) at 800 rpm was obtained when stationary, 69.3 dB(A) at 1500 rpm rpm and 74.44 dB(A) at 2000 rpm.
- Special purpose vehicles have higher interior acoustic pressure values than classic off-road vehicles, which is also due to their special purpose.
- The acoustic background associated with the passenger compartment of the vehicle both in motion and stationary, in the test conditions, continuously contributes to the noise profile perceived by the passengers.
- At the same time, the interior acoustic pressure values are not an indicator of acoustic comfort, but they are constitutive in determining it.
- In the operation of motor vehicles on public roads, transient sources (such as traffic) will contribute significantly to the noise profile in the cabin perceived by passengers, leading to values that exceed the permissible limits.
- The noise variations determined as a result of the experimental measurements in the passenger compartment of the vehicle lead to discomfort and have harmful effects on the passengers. A noise level between 35-70 dB, for a long time, to which the driver of a vehicle can be subjected leads to the appearance of fatigue, impaired vision, difficulty in understanding speech and even causes headaches for a noise level exceeding the value of 70 dB.
- A monitoring and measurement strategy is presented as well as important data regarding the acoustics of the passenger compartment of special purpose vehicles, together with the selection of the best available techniques, with the aim of contributing to the further mitigation of the potential sound impact on passengers, as well as the implementation of a strategies to improve the indoor acoustic comfort level.

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