

THE MOTOR VEHICLE EXHAUST AND INTAKE SYSTEM CHARACTERIZATION BY DINT OF CEPSTRUM ANALYSIS

ХАРАКТЕРИСТИКА НА ОТРАБОТЕНИТЕ ГАЗОВЕ И ВСМУКАТЕЛНАТА СИСТЕМА ПРИ МОТОРНИ ПРЕВОЗНИ СРЕДСТВА ПОСРЕДСТВОМ КЕПСТРАМ АНАЛИЗ

Zoran Jovanović, Željko Šakota, Zoran Masoničić, Siniša Dragutinović, Zlatimir Živanović¹

Abstract – *In this paper some ab initio results concerning the noise analysis of intake and exhaust systems of commercial vehicles manufactured by FAP Corporation are presented. The hybrid experimental-theoretical method is used for the efficiency analysis of the exhaust and intake system subjected to the conditions of accelerating vehicle („pass-by“) test. The bunch of results obtained elucidate the clear distinction between acoustic potential and acoustic efficiency of the solutions that incur i.e. the clear difference between quantitative and qualitative characterization of these systems.*

1. INTRODUCTION

Acoustic properties of the exhaust system can be described by transmission characteristics /1, 4, 5/, which represents the general tool for the characterization of linear system properties. Transmission characteristics of the exhaust system designates the relationship between the acoustic power of the input signal and the acoustic power of the output signal for the whole range of the frequencies concerned. This characteristics describes system properties that are invariant with regards to the system working conditions i.e. as regards engine acoustic impedance value and the radiation impedance value at the system output. Sooth to say the exact determination of the output acoustic impedance value of the engine is inordinately hard task yielding certain difficulties in the theoretical description of the motor vehicle exhaust system behaviour with given transmission characteristics thereafter. It means that the engine characteristics is the prerequisite condition for the muffler design even in the case when transmission characteristics is known in advance /3, 7, 8/.

The exhaust system insertion loss characteristics represents the difference between the acoustic pressures at certain point of the space in the case when the exhaust system is dismantled and the acoustic pressure at that point when the exhaust system is installed. Therefore all signals indispensable for the exact determination of the insertion loss characteristics can be easily measured. However, the determination of the insertion loss characteristics for the sake of the exhaust system behaviour description in real conditions is inordinately hard task due to well known below listed difficulties. Namely its known for a while that certain limitations as regards the reproduction of the identical working regimes in both cases i.e in the case when the exhaust system is installed and in the case when it is dismantled are encountered. In addition, the insertion loss characteristics of the pertinent exhaust system is not the same for all working regimes due to excessive acoustic pressure at the input yielding the detention of the linear behaviour of the system thereafter. Transsmition loss characteristics is inherent solely to the geometry layout of the particular exhaust system. This

characteristics is not subjected to alterations either due to inclusion of various additional components in the whole chain or due to excitation source and load variations. At the other hand, the insertion loss is highly dependant on the impedance value of the engine. Namely, for the prediction of the acoustic pressure at the exhaust outlet not only the determination of excitation source (impedance value and load of the engine) but also the acoustic pressure is indispensable./6, 9/.

In this paper the determination of the insertion loss characteristics of the particular exhaust/intake system is elucidated. Namely, fast spectra variations ensuing primarily from engine operations were annihilated in cepstral domain yielding the elimination of the effect of the nonidentical operating conditions of the engine in the case with and without exhaust/intake system respectively. Insertion loss characteristics variations with regards to different operating conditions of the engine were tackled to as well.

2. THE ACUSTIC PRESSURE MEASUREMENTS FOR THE SAKE OF THE INSERTION LOSS SPECTRA DETERMINATION

Insertion loss characteristics of the system (IK) is defined as the ratio between pressure p_2' which represents the acoustic pressure at the exhaust pipe outlet when the exhaust system is dismantled and pressure p_2 which represents the acoustic pressure at the exhaust pipe outlet when the exhaust system is installed.

$$IK = 20 \log(p_2' / p_2) \quad (1)$$

Pressure p_2 consists of forward wave p_{2+} and backward wave i.e the wave that reflects from the end of the pipe p_{2-} , so pressure ratio can be given as follows

$$p_2' / p_2 = \frac{(p_{2+}' + p_{2-}')}{(p_{2+} + p_{2-})} = \frac{p_{2+}'}{p_{2+}} \cdot \frac{(1-R')}{(1-R)} \quad (2)$$

For the same radius of the pipe reflection coefficients R i R' are equal so it follows

$$p_2' / p_2 = \frac{p_{2+}'}{p_{2+}} \quad (3)$$

¹ INN Vinča, Department for motor vehicles and engines, p.fah 522, 11001 Beograd

signal $i(n)$ it can be separated by dint of detection of cepstrum components for $n < T$ the cepstrum of the impulse response and spectral characteristics of the system. In fact in this way higher components of the cepstrum ensuing from excitation source which constitute fast variable harmonic spectrum are annihilated. The rest of the cepstrum, its lower parts, define slowly variable part of spectrum, i.e. its envelope.

In the case when excitation signal is composed of sequence of impulses with the period T and when its spectrum is harmonic and flat after passing through the system then the signal is modulated with the spectral characteristics of the system and represented as the envelope of the spectrum of the resulting signal. In the case when excitation signal is entirely different (in this paper) the envelope of the spectrum represents the characteristics of the system with the inclusion of the spectral characteristics of the excitation impulse $e(n)$, i.e. the characteristics of one period of excitation signal.

4. THE INTAKE AND EXHAUST SYSTEM ANALYSIS

Determination of the insertion loss characteristics from the p_2 and p_2' spectra is inordinately hard assignment due to complications related to the achievements of identical operating conditions in cases when exhaust system is dismantled and installed respectively. It should be noted that the exhaust system has a great influence on the operating conditions of the vehicle. In the case of spectra obtained even for the same engine speed some spectral peaks in insertion loss characteristics inherent to elusive conditions are encountered. Noncoinciding periodicities in signals p_2 and p_2' were discarded by dint of homomorphic analysis.

In one moment of time, for a given engine speed, one part of the $p_2(n)$ signal has been separated (point A, fig. 4.1) by dint of Hamming's window $w(n)$ whose length is 1000 parts. After that DFT has been applied, point B, and then in point C the spectrum module and its logarithm $[P_2(j\omega)]_{db}$ have been calculated. Using the IDFT in point D the cepstrum is obtained. According to the previously mentioned, in this point there is a possibility to excerpt system characteristic $h(n)$ and one excitation impulse $e(n)$ from the periodic impulse. Using the window of 70ms length, only the lower part of the cepstrum that contains characteristics of the only one excitation impulse-one exhaust cycle has been excerpted while the rest of the cepstrum has been annihilated. The length of the cepstrum window (7 ms) is smaller than duration of the excitation impulse, i.e. duration of the one exhaust cycle, and, schematically, is shown in fig.4.2. During the first 6.5 ms window is flat and then it decreases like $\cos(t/6)$. Using the DFT, in point E, resulting spectrum $[P_2e(j\omega)]_{db}$ has no harmonic structure because all upper components of the cepstrum ensuing from the periodic impulse and define its application, have been excluded.

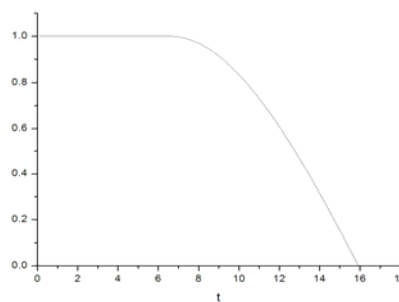


Fig. 4.2 Cepstrum window

In entirely the same way $[P_2'(j\omega)]_{db}$ and $[P_2e'(j\omega)]_{db}$ spectrums addicted to the acoustic pressure signal p_2 are obtained for the case when exhaust system is not installed. Insertion loss characteristic is determined by the difference of these two spectra $[P_2'(j\omega)]_{db}$ and $[P_2e'(j\omega)]_{db}$.

In this way, insertion loss characteristics for multiple moments of time, i.e. multiple different working regimes can be determined (the obtained signal comes from the accelerating vehicle).

Fig. 4.3 represents the described signal spectrums p_2 i p_2' in two moments when the number of engine p_2 is approximately equal and corresponding insertion loss characteristic $[IK(j\omega)]_{db} = [P_2e'(j\omega)]_{db} - [P_2e(j\omega)]_{db}$, for the commercial vehicle designated as FAP 1926.

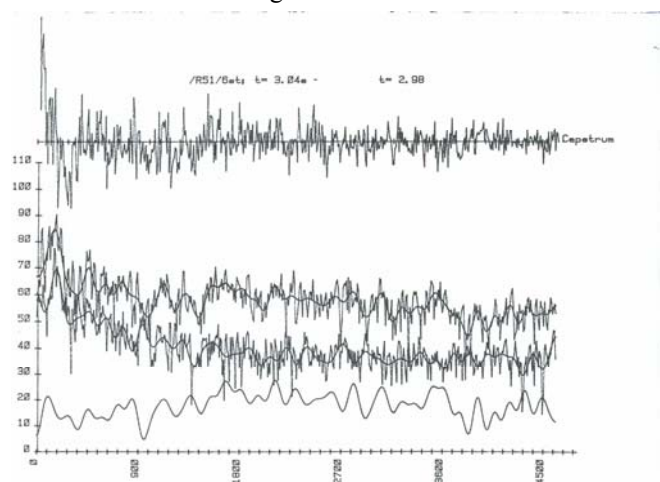


Fig. 4.3. Insertion loss characteristics of the exhaust system of the vehicle FAP 1926

In order to determine the relationship between insertion loss characteristics and engine working regime, this analysis has been carried out for multiple moments of time, i.e. multiple working regimes. For example, in the case of one vehicle tested (FAP 1926), this analysis has shown that insertion loss characteristics is invariant as regards engine operating conditions (obviously the acceleration of the vehicle ensuing from the increase of engine speed has not affected the insertion loss characteristics of exhaust/intake system). Insertion loss characteristics depicted in fig. 4.3 shows that method of cepstrum analysis applied is fairly good for the characterization of exhaust/intake systems. The particular insertion loss characteristics shows relatively unacceptable attenuation in low frequency range indicating the acoustic potential of the muffler. Namely significant improvement can be achieved by reconfiguration of acoustic elements within the exhaust system. Average insertion loss, in frequency range of 4500 Hz, is about 20dB which, of course, is not impressive

result. It should be noted that attenuation in low frequency range is fairly complicated and constrained with geometry layout of acoustic components (pipe and tube length, number of chambers in muffler etc).

The same technique is applied on the large number of commercial vehicles from the product range of MDD FAP Priboj corporation and fig. 4.4 represents insertion loss characteristics for the exhaust system installed in vehicle designated as FAP 2226.

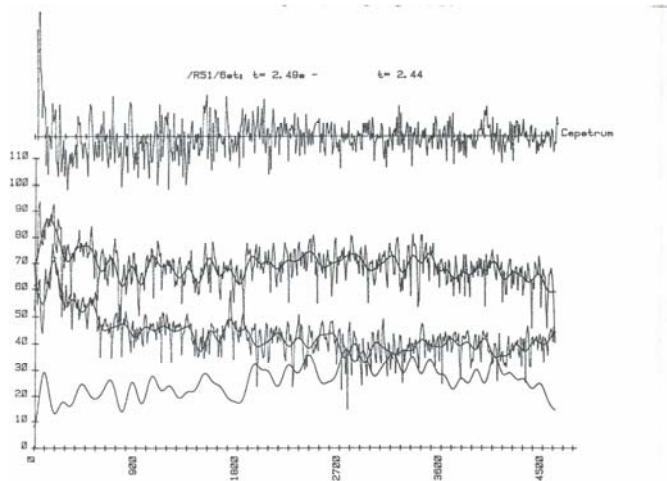


Fig 4.4. Insertion loss characteristics of the exhaust system of the vehicle FAP 2226

It is obvious that insertion loss characteristics of this muffler is better in whole frequency range and numerical value (average value in whole frequency range considered is 25.14dB) is very close to the acoustic potential of the system (small improvements in domain of combustion noise). The excessive attenuation in high frequency range is inherent to the dissipative exhaust mufflers and doesn't have an influence on the overall exterior noise level such as that in low frequency range (acceptable-average value up to the 1000 Hz is in excess of 21dB). In exactly the same way intake systems could be analyzed and compared. Fig.4.5 shows insertion loss characteristics for the intake system of the same vehicle whose exhaust system characteristics is shown in fig. 4.3 (vehicle FAP 1926).

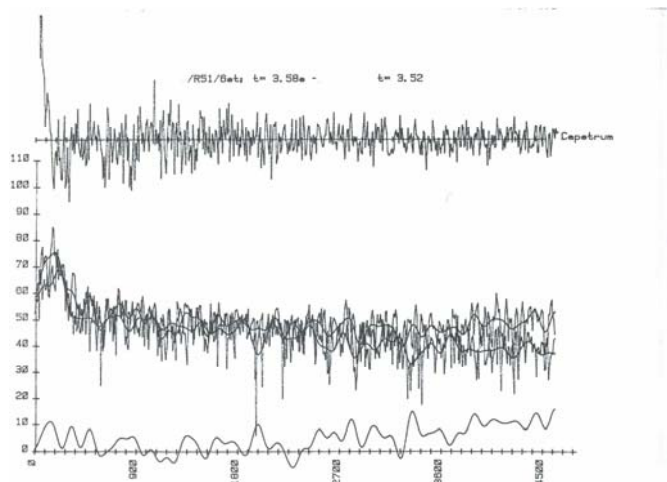


Fig 4.5. Insertion loss char. of the intake system FAP 1926

Taking into account the numerical value of the maximum overall exterior noise level of the vehicle and the contribution of this in principle predominant noise source to the overall

exterior noise level of the vehicle the average value of 6.18 dB in whole frequency range is fairly acceptable. Ripples in the vicinity of zero value in frequency interval ranging from 1000 to 2500 Hz indicate that no consideration of noise was taken into account during the design of this system.

REFERENCES

- [1] A.Y.Sathyanarayana, M.L.Munjal „A hybrid approach for aeroacoustic analysis of the engine exhaust system“, Applied Acoustics 60 (2000) 425-450
- [2] A.Broach, J.R Serrano, F.J.Arnau, D.Moya „Time domain computation of muffler frequency response: Comparison of different numerical schemes“, Journal of Sound and Vibration 305 (2007), 333-347
- [3] A.Broach, X.Margot, A.Gil, F.D.Denia „A CFD approach to the computation of the acoustic response of exhaust mufflers“ Journal of Computational Acoustics, vol 13, No 2(2005), 301-316
- [4] O.Chiavola „Multidimensional CFD transmission matrix modeling of IC engine intake and exhaust system“, Journal of Sound and Vibration (2002) 256 (5), 835-848
- [5] T.W.Wu, P.Zhang „Boundary element analysis of mufflers with an improved method for deriving the four pole parameters“, Journal of Sound and Vibration (1998) 217 (4), 767-779
- [6] E.Dokumaci „Prediction of source characteristics of engine exhaust manifolds“, Journal of Sound and Vibration 280 (2005), 925-943
- [7] P.O.A.L. Davies „Piston engine intake and exhaust system design“, Journal of Sound and Vibration (1996) 190(4), 677-712
- [8] M.Y.Crocker „IC Engine exhaust muffling“, NASA Langley Research Report NASA-CR-2324, 1987
- [9] M.G.Prasad, M.J.Crocker „Insertion loss studies on models of automotive exhaust systems“, Journal of Acoustical Society of America, 70 (5), Nov. 1981
- [10] „Uniform provisions concerning the approval of motor vehicles having at least four wheels with regard to their noise emissions“, Regulation No.51, E/ECE/324, E/ECE/TRANS 505, UN