ACTIVE NOISE CONTROL TECHNIQUE FOR DIESEL TRAIN LOCOMOTOR EXHAUST NOISE ABATEMENT

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ABSTRACT

An original prototype for train locomotor exhaust noise reduction (electronic muffler - EM) is proposed: the system is based on an active noise control technique. An acoustical measurement campaign has shown that locomotor exhaust noise is characterized by very low frequency components (less than 80 Hz) and very high acoustic power (up to 120 dB). A custom EM, characterized by high acoustical efficiency at very low frequencies has been designed and realized at Perugia University Acoustic Laboratory; it has been installed on an italian D.245 train locomotor, equipped with a 500 kW diesel engine. EM has been added to the traditional passive muffler. Very low transmission losses are introduced by EM because of its particular shape; thus, engine efficiency does not decrease. Cancelling noise is generated by means of DSP based numerical algorithm. Disturbing noise and cancelling noise destructively interfere at the exhaust duct outlet section; outgoing noise is thus reduced. The control system reduces exhaust noise both in steady and unsteady engine regime. Measurements results have shown that EM introduces up to 15 dB noise abatement in 31.5-63 Hz frequency range.

1. INTRODUCTION

Exhaust noise abatement is usually obtained by passive mufflers [1]. Active control noise prototypes have been proposed to extend noise reductions to low frequencies components [2]. An active control system (electronic muffler - EM) for train locomotor exhaust noise abatement is here proposed. An acoustical measurement campaign has shown that train locomotor exhaust noise emissions are characterized by high acoustic power levels (120 dB at maximum engine regime) and very low frequency components. Noise main component frequency, which depends on engine regime, belongs to 31.5-63 Hz range. An EM prototype has been designed and realized at Perugia University Acoustic Laboratory. It has been installed on an Italian D.245 diesel train locomotor. EM has been added to the D.245 passive muffler stage. EM introduces very low transmission losses because the EM exhaust duct is an empty and straight duct. A custom acoustical source has been designed in order to generate an high power very low frequencies cancelling signal. Cancelling signal is generated by a DSP control unit which implements an adaptive FxLMS algorithm. Reference and error signals (DSP input signals) are derived by two microphones which are installed respectively upstream and downstream the EM exhaust duct. Exhaust noise and cancelling signal destructively interfere at the exhaust duct final section. The microphones have been connected to the muffler by means of flexible ducts; thus, DSP input signals are not affected by high frequency components due to the structural vibrations. The cancelling signal loudspeaker and the microphones have been protected against dusty and hot exhaust gases by means of thermal insulation slices. An acoustical measurement campaign has been carried out in order to test EM performances. Measurements results have shown a 3dBA global noise reduction and a main noise components reduction higher than 12dB for each engine rpm.

2. TRAIN LOCOMOTOR NOISE EMISSIONS

The D.245 italian train locomotor characteristics are:
- 500 kW diesel engine;
- 9240 mm locomotor length;
- 1040 mm drive wheels diameter;
- 48000kg locomotor weight;
- 65 km/h maximum speed;
- 600 rpm minimum engine regime;
- 1200 rpm maximum engine regime.

Noise power levels have been evaluated by means of an intensimetric measurements campaign for different rpm regimes [3]. Twenty measurement points have been considered on an imaginary parallelepiped surface which surrounds the noise source. Power levels spectra at minimum and maximum engine rpm are respectively shown in Figs 1 and 2.

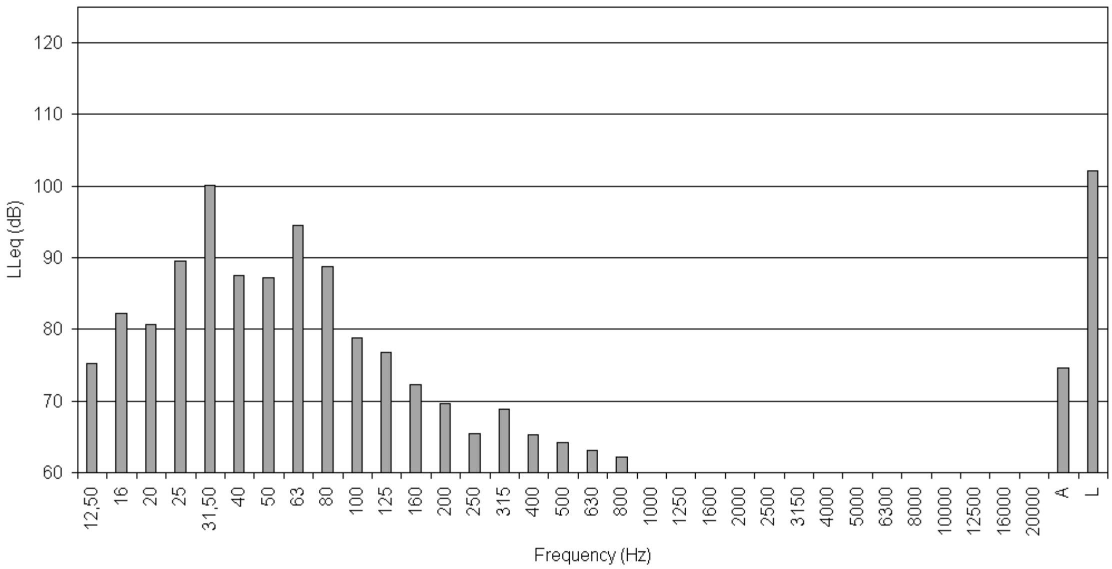

Fig. 1: D.245 power spectrum at 600 rpm (minimum engine regime)

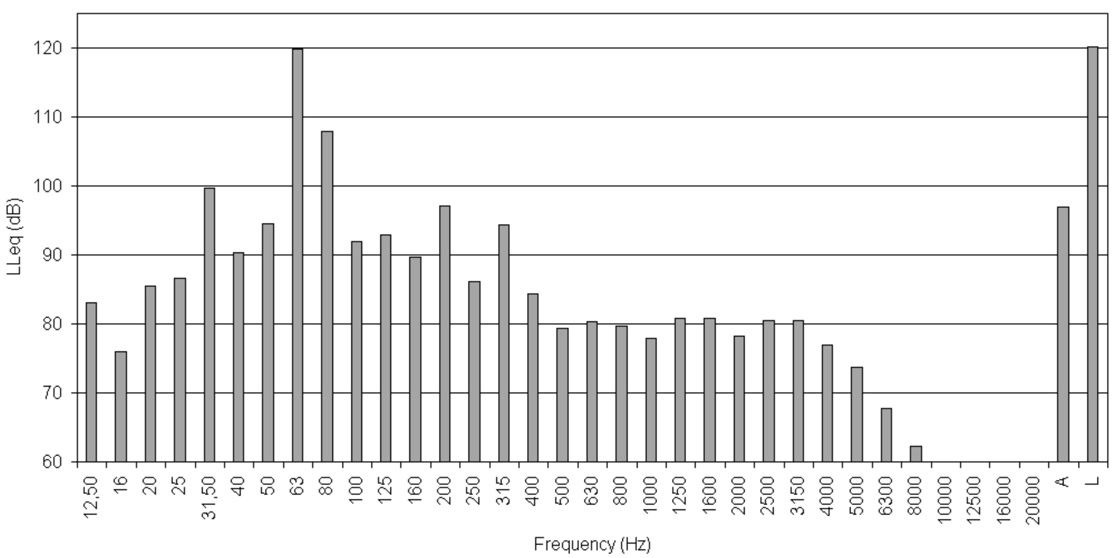

Fig. 2: D.245 power spectrum at 1200 rpm (maximum engine regime)

By observing Fig. 1 and Fig. 2, noise power level is 120dB and 102dB, respectively at 1200 rpm and 600 rpm. Main noise component (MNC) frequency is 63 Hz at 1200 rpm and 31.5 Hz at 600 rpm.

3. THE ELECTRONIC MUFFLER

The proposed active control muffler (EM) is sketched in Fig.3. Engine noise signal propagates inside the exhaust pipe [4]. A particular acoustical source generates cancelling noise which propagates into a duct which coaxially surrounds the exhaust gas one.

The acoustical source characteristics are:

- accelerometer based control system for reduction of low frequencies distortion due to loudspeaker diaphragm movement inaccuracies;
- 32 cm diameter sub-woofer characterized by high efficiency at 20-120 Hz frequency range;
- 1250W rms (3000W peak) amplifier.

Primary and cancelling noises destructively interfere at the EM duct final section (see Fig. 3) [5]. In order to achieve the best acoustical matching between cancelling noise source and EM final section, cancelling noise duct section has been gradually varied (impedance adapter stage in Fig. 3) to obtain a circular shape final section which matches external acoustical impedance. EM final section dimensions have been designed in order to equalize cancelling noise and primary noise acoustic flow rate, which respectively are 0.16 m^3/s and 0.15 m^3/s.

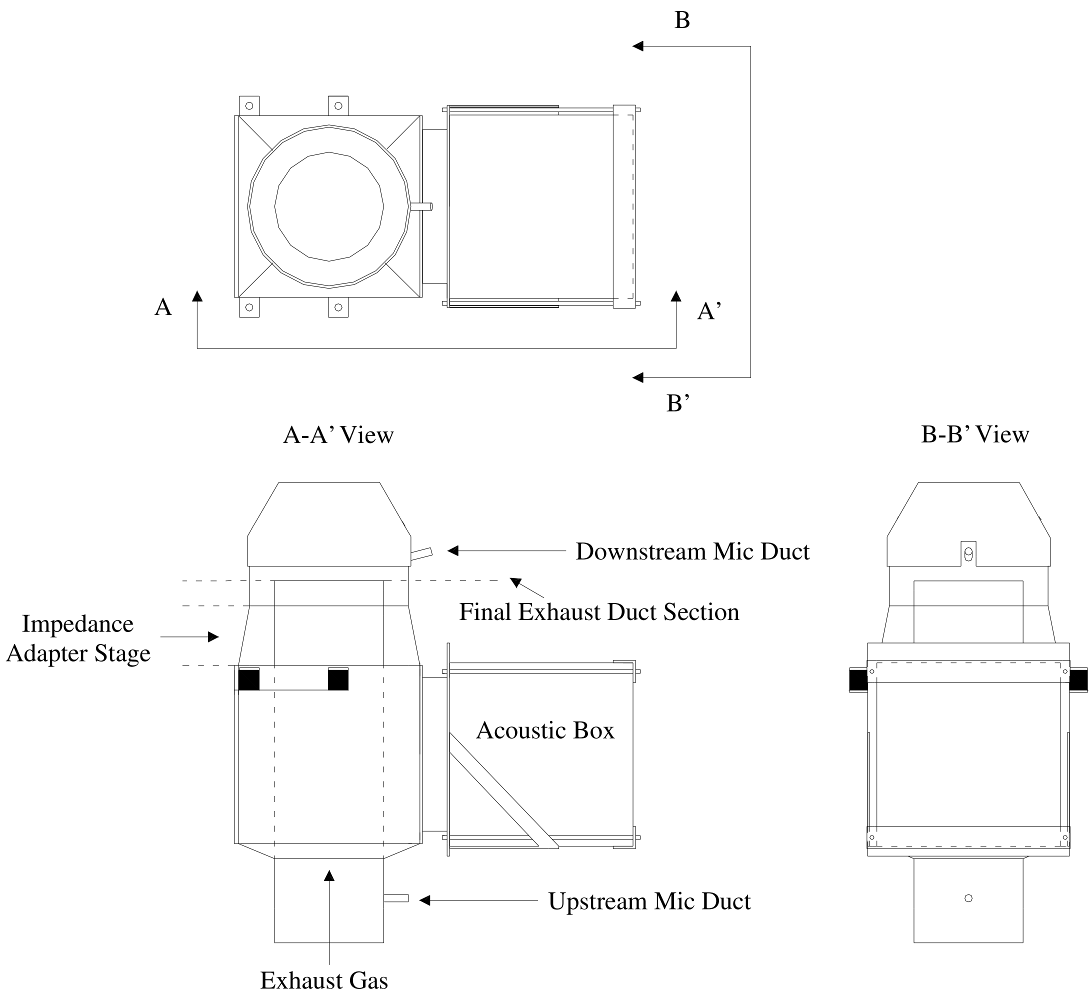

Fig. 3: EM scheme.

The acoustical source is fed by a DSP control unit. The control unit implements a Filtered-x LMS control algorithm [6].

Two small ducts (50 millimetres length, 15 millimetres diameter) have been realized upstream and downstream the electronic muffler. Two microphones are put into the two ducts. The upstream microphone picks up a reference signal which is synchronized with exhaust noise. The downstream microphone picks up the error signal. Control unit algorithm processes reference and error signals to generate cancelling signal.

EM prototype has been realized at Perugia University Acoustic Laboratory and it has been installed to the D.245 exhaust pipe (see Fig. 4). EM has been added to the passive muffler. EM introduces very low transmission losses because of its particular shape.

Fig. 4: EM connected to the D.245 exhaust pipe.

4. TEMPERATURE AND MECHANICAL VIBRATIONS PROBLEMS

Peculiar solutions have been adopted to skip the following technological problems:

A) the loudspeaker and the microphones are subjected to dusty and hot exhaust gases;

B) the microphones pick up signals affected by high frequency components due to the locomotor mechanical vibrations, especially for great engine rpm.

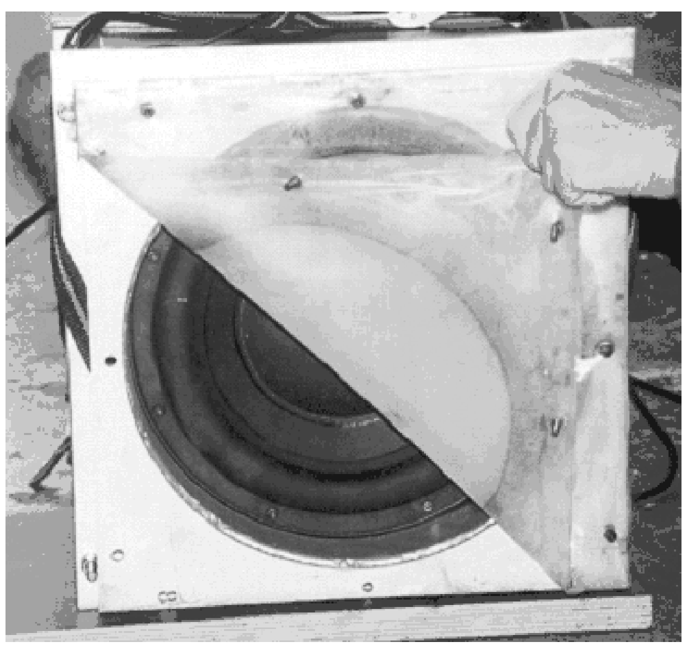

Fig. 5: cancelling source protected by the silicone slice

In order to solve A) problem, a temperature measurement campaign has been led: when the engine regime is 1200 rpm, maximum temperature of loudspeaker frame and microphones external surface is 80°C; such a condition may cause damages to the loudspeaker diaphragm and microphones membranes. In order to protect the loudspeaker diaphragm, a 0.5 mm thick silicone slice has been sandwiched between the loudspeaker and the EM cancelling duct (see Fig. 5). Microphones have been separated from direct gas flow with a thermal insulation slice (0.035 W/mK thermal conductivity, 150°C maximum operative temperature), which introduces no acoustic distortions. Microphones and thermal insulation slice are held together thank to 9cm length brass tubes.
In order to solve B) problem, brass tubes have been connected to the exhaust gas duct thank to two flexible junctions which are realized in EPDM coated by steel wire pattern. Thus, microphones are vibrationally separated by the muffler walls. Microphones protection systems are shown in Fig. 6a and 6b.

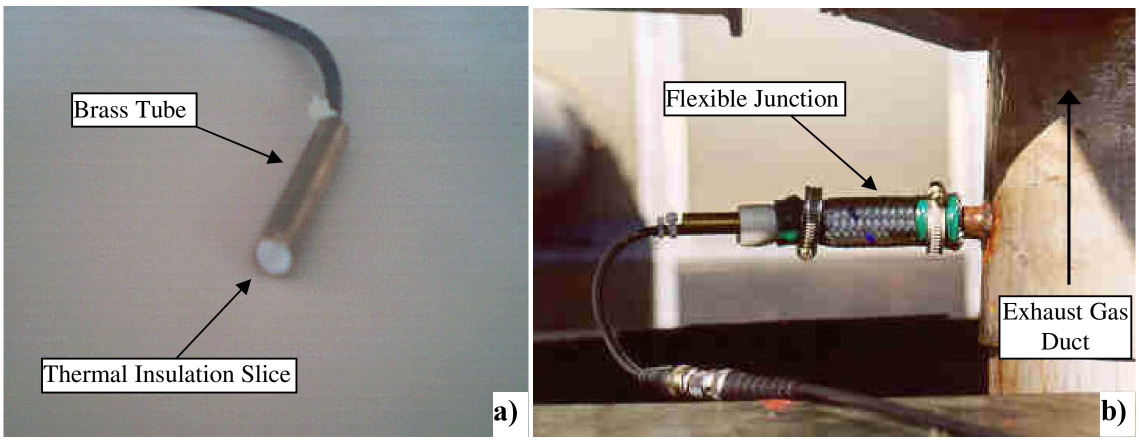

Fig. 6: a) microphone thermal protection system; b) reference microphone connection

5. ELECTRONIC MUFFLER ACOUSTICAL PERFORMANCES

A measurement campaign has been led in order to test EM acoustical performances. Noise level measurements have been carried out for different engine regimes. Investigator 2260 phonometer, by Bruel & Kjaer, equipped with the model 4189 microphone, by Bruel & Kjaer, have been employed. Measurement points, shown in Fig. 7, lies on a plane which is 4 m height from ground.
A temperature sensor has been installed in the air volume between the silicone protection and the loudspeaker diaphragm. A 40°C maximum temperature has been measured: no loudspeaker damage due to thermal causes occurs. Measurements have been carried out for a 30 seconds time interval; equivalent noise level (L_{eq}) and A-weighted equivalent noise level (L_{Aeq}) have been measured. Noise level comparisons are reported for the two most practiced engine regimes:

- 600 rpm (minimum engine regime, parking activities), which determines the lowest main 1/3 octave band noise component (MNC), that is 31.5 Hz;
- 1200 rpm (maximum engine regime, track activities).

L_{eq} and L_{Aeq} values and the MNC level are reported in Tab. 1 for control on (ON) and control off (OFF) conditions. Global noise average reductions are 6.7 dB for both 600 rpm and 1200 rpm when the active control system is ON with respect to OFF condition. The A-weighted noise reductions are 2.6 dBA for 600 rpm and 3.2 dBA for 1200 rpm while the average MNC reductions are 13.1 dB for 600 rpm and 13.3 dB for 1200 rpm.
The maximum reduction is measured in L, M and N points and the minimum one in A point. It is expected that noise reduction values tends to MNC reduction ones as evaluation distance grows, because low frequency components better propagate than the other ones. Global noise A-weighted reduction is lower than linear one because control system performs the highest noise reductions at low frequencies. Thus, A-weighted noise reductions for 600 rpm are lower than the ones for 1200 rpm because the 600 rpm MNC (31.5 Hz) is lower than the 1200 rpm one (63 Hz). A measurement campaign has also been carried out for an unsteady engine regime cycle. Unsteady cycle is constituted by 20 seconds time interval: the first 10 seconds in acceleration engine regime (from 600 rpm to 1200 rpm), the second time interval in deceleration engine regime (from 1200 rpm to 600 rpm). Measurements results have shown in Tab. 1. Unsteady cycle global noise average reduction and A-weighted average noise reduction are respectively 6.7 dB and 2.8 dBA.

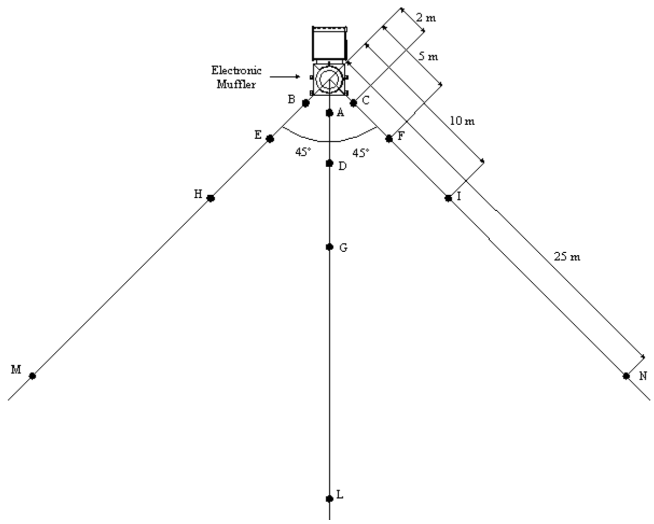

Fig. 7: measurement points positions.

Tab. 1: EM L_{eq} and L_{Aeq} values for 600, 1200 rpm and unsteady cycle engine regimes in control on (ON) and control off (OFF) conditions. Noise level reductions (Δ) obtained by means of the active control system.

Measurement points	*Engine rpm*	*Equivalent noise level L_{eq} [dB]*			*A-weighted noise level L_{Aeq} [dBA]*			*MNC level (31.5 Hz at 600 rpm, 63 Hz at 3000 rpm)[dB]*		
		Control system		Δ	Control system		Δ	Control system		Δ
		OFF	ON		OFF	ON		OFF	ON	
A	600	101.5	95.5	6.0	74.0	72.0	2.0	98.0	86.5	11.5
	1200	112.0	106.5	5.5	92.0	89.5	2.5	111.5	99.5	12.0
	Unsteady	105.0	100.0	5.0	82.5	80.5	2.0	-	-	-
B	600	101.0	95.0	6.0	74.0	72.0	2.0	98.5	86.5	12.0
	1200	113.0	106.5	6.5	92.5	89.5	3.0	112.0	100.0	12.0
	Unsteady	105.5	99.5	6.0	83.0	80.5	2.5	-	-	-
C	600	102.5	96.5	6.0	76.0	73.5	2.5	100.5	88.0	12.5
	1200	113.5	107.5	6.0	92.5	89.5	3.0	113.0	100.5	12.5
	Unsteady	106.0	100.0	6.0	83.0	80.0	3.0	-	-	-
D	600	97.0	90.5	6.5	70.5	68.0	2.5	94.5	82.0	12.5
	1200	106.5	100.0	6.5	87.5	84.5	3.0	105.5	92.5	13.0
	Unsteady	103.0	96.5	6.5	79.5	77.0	2.5	-	-	-
E	600	96.5	90.5	6.0	70.5	68.5	2.0	94.5	82.5	12.0
	1200	107.0	101.0	6.0	88.5	86.0	2.5	106.0	93.0	13.0
	Unsteady	102.5	96.0	6.5	79.0	76.5	2.5	-	-	-
F	600	98.0	91.5	6.5	72.5	70.0	2.5	96.5	84.0	12.5
	1200	108.0	102.5	5.5	89.5	87.0	2.5	107.5	95.0	12.5
	Unsteady	103.0	97.0	6.0	80.0	77.5	2.5	-	-	-
G	600	93.0	86.5	6.5	66.5	64.0	2.5	91.5	78.5	13.0
	1200	100.5	94.0	6.5	82.5	79.5	3.0	99.5	86.0	13.5
	Unsteady	96.5	99.5	7.0	74.5	72.0	2.5	-	-	-
H	600	93.5	86.5	7.0	67.5	65.0	2.5	92.0	78.5	13.5
	1200	102.0	95.0	7.0	84.0	80.5	3.5	100.5	87.5	13.0
	Unsteady	96.0	99.5	6.5	74.0	71.0	3.0	-	-	-
I	600	94.5	88.0	6.5	68.0	65.0	3.0	92.5	79.0	13.5
	1200	101.0	94.0	7.0	83.5	80.5	3.0	100.0	86.0	14.0
	Unsteady	97.0	90.0	7.0	74.0	71.0	3.0	-	-	-
L	600	73.5	65.5	8.0	54.5	51.5	3.0	71.0	56.5	14.5
	1200	86.0	78.5	7.5	69.0	65.0	4.0	85.0	70.5	14.5
	Unsteady	81.5	73.5	8.0	61.5	58.0	3.5	-	-	-
M	600	75.0	67.0	8.0	56.0	52.5	3.5	71.5	56.5	15.0
	1200	88.0	80.0	8.0	70.5	66.0	4.5	86.5	71.5	15.0
	Unsteady	80.5	72.5	8.0	62.0	58.5	3.5	-	-	-
N	600	75.5	68.0	7.5	57.0	54.0	3.0	73.0	58.0	15.0
	1200	87.5	79.5	8.0	70.5	66.5	4.0	86.5	71.5	15.0
	Unsteady	80.5	73.0	7.5	63.0	59.5	3.5	-	-	-

6. CONCLUSIONS

An active control noise muffler (EM) for train locomotor exhaust noise reduction is proposed. The noise emissions of an Italian D.245 locomotor have been evaluated by means of a measurement campaign. Measurements results have shown that the locomotor exhaust noise is characterized by high power levels and very low frequency components (31.5-63 Hz range). Thus, an acoustical source characterized by high power and high efficiency at very low frequencies is needed to generate the cancelling signal. Cancelling signal is obtained by a DSP control unit; DSP input signals are derived by two microphones which are placed upstream and downstream the exhaust pipe. The destructive interference between the cancelling and the exhaust noise occurs at the exhaust pipe outlet. The acoustical source and the microphones have been protected by dusty and hot exhaust gases by means of custom solutions: the microphones have been installed to EM by means of flexible junctions in order to reduce the influence of locomotor vibrations on picked up signals. An acoustical measurement campaign has been led to evaluate the EM noise abatement: EM average noise abatement is 6.7 dB for both minimum (600 rpm) and maximum (1200 rpm) engine regime. Such noise reduction have been obtained both in steady and unsteady engine regime conditions. Main noise component reduction is up to 15dB for each engine regime, which corresponds to 31.5-63 Hz frequency range. Results demonstrates that EM may be conveniently employed together with a passive traditional muffler in order to extend noise reduction to very low frequency components.

7. LIST OF SYMBOLS

Symbol	Unit/Meaning	Description
Δ	dB/dBA	Noise level reductions
EM	Acronym	Electronic Muffler
L_{eq}	dB	Equivalent noise level
L_{Aeq}	dBA	A-weighted noise level
MNC	Acronym	Main Noise Component
rpm	Acronym	Revolutions per minute

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