Prospects and Limits of Common- and Differential-Mode Separation for the Filter Development Process

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***Abstract*—A common way to describe conducted electromagnetic disturbances is to separate the measured noise voltages into common- and differential-mode. To design an appropriate EMI line filter the noise impedance has to be considered during the development process. The described method uses the practical approach to determine the common- and differential- noise impedances to calculate the filter attenuation up to 108 MHz for automotive applications. This article gives an overview on how to use disturbance decomposition and shows the limits of the mode separation procedure for the filter development process.**

common- differential-mode, noise impedance, filter development, noise source description

I. Introduction

The design of filters for given limit values in the frequency domain is well known in signal processing tasks. However, the procedures are not directly assignable to reduce the conducted emissions with line filters due to the four port behavior of the filter structures. Especially within automotive engineering, for power devices and control units, the filter has to reduce conducted noise up to 108 MHz to meet the CISPR regulatory standards.

In general, conducted emissions can be separated into common- and differential mode [1], [2]. With the help of the mode information, the filter elements can be chosen as a result of the predominant disturbing mode. Although mode decomposition can help to set up the filter structure, the complete filter development process is not trivial for two reasons:

- internal assembly of the DUT (device under test) is often unknown to EMC engineers
- input impedance of the device over the considered frequency is unknown.

Moreover, the interaction between the DUT and the power line filter cannot be considered and can cause insufficient noise attenuation. The lack of information leads therefore to a number of trial and error attempts to meet the automotive EMC standards.

Numerous methods of how to develop an appropriate EMI- filter are available e.g. [3], [4]. Unfortunately, only limited research has been carried out on how to consider the input impedance of the DUT within the development process. Furthermore, existing techniques usually ignore the noise impedance of the DUT. Available methods are limited to a couple of MHz, resulting out of the main problems at working frequencies for switched-mode power supplies (SMPS). Encouraged by [4] and [5], a method is developed how to determine the common- and differential-mode noise impedances of an arbitrary system and how to use the results to calculate the filter attenuation in accordance with the setup out of CISPR25. The limit of using common- and differential-mode decomposition for the filter development process is reached whenever an asymmetric filter structure is used, as described in section VII. Mode conversion within the filter leads to an interaction between the used common- and differential-mode equivalent circuits and thus limits the use of the emission decomposition.

II. General Setup

Fig. 1 shows the measurement setup to separate the common- and differential-mode voltages. The LISN box is equivalent to the line impedance stabilization network, described in [6].

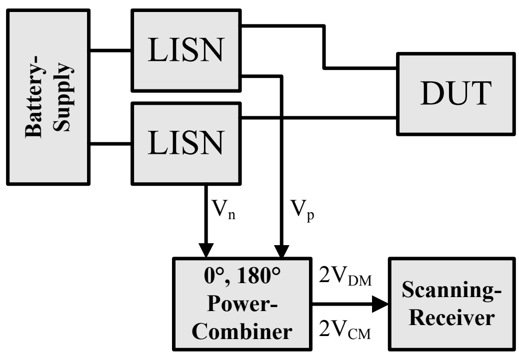


Figure 1. General setup to separate conducted emissions into common- and differential-mode

Although the following procedure is described for automotive applications, every step can be transferred to AC power systems.

To separate the common- (V_{CM}) and differential-mode (V_{DM}) voltages, two power combiners are used to add and subtract the line voltages V_p and V_n according to equations (1) and (2).

$$2\,V_{CM} = V_p + V_n \quad (1)$$
$$2\,V_{DM} = V_p - V_n \quad (2)$$

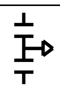
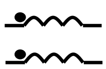
It is also possible to use a pair of high-quality 1:1 transformers to add or subtract the line voltages [1]. With the correction factors for common- and differential-mode, the scanning receiver displays the common- and differential noise voltages.

III. Filter Development

A. Selecting Appropriate Filter Elements

With the knowledge of the dominant noise source mode, an appropriate filter structure can be applied to the system. In general, four different subtypes of structures within a filter are available. Table I shows the available subtypes in respect to the impact of the possible noise modes and mode conversion.

TABLE I. POSSIBLE FILTER STRUCTURES

Mode / Structure		DM	DM to CM	CM	CM to DM
	X	■	▪	▪	▪
	L	■	■	■	▪
	Y	■	▪	■	▪
	CMC	▪	▪	■	▪

Possible filter elements are represented by so called X- and Y-capacitor structures as well as series inductance (L) and common-mode chokes (CMC).

The large dots indicate the ideal influence of the subtypes in respect to the well-known equivalent circuits shown in figure 3. An X-capacitor impacts only differential-mode (DM) voltages whereas a common-mode choke only influences to common-mode (CM). Series inductance is not only damping both modes but also enforces a differential- to common-mode conversion (DM to CM).

The smaller dots show the influence of the subtypes due to parasitic elements. Parasitic elements, e.g. asymmetry within a common-mode choke, are influencing all possible modes. The same effect applies for Y-structures with unbalanced elements or different length of PCB tracks.

For the first dimensioning of the filter, the parasitic behavior of the subtypes can be neglected and only ideal mode attenuation has to be considered in respect to the dominant noise mode [1], [4].

B. Determining the Common- and Differential-Mode Input Impedance

To determine the common- and differential-mode input impedance, four independent measurement results are necessary. First, the noise spectrum without any filter structure is considered for common- and differential-mode. Within the next step, a known filter structure is connected to the DUT, see figure 2. In order to table I, only structures without mode conversion can be used. The best choice is made with the Y-capacitor structure. This structure will both affect common- and differential-mode; however, no mode conversion occurs when exactly the same elements are used with symmetric connections. Figure 3 shows the resulting common- and differential-mode equivalent circuits. The impedance of the capacitors C_m within the Y–structure are represented through their equivalent impedance Z_m.

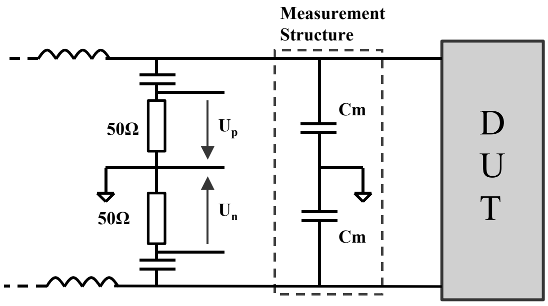


Figure 2. Equivalent circuit for the setup with Y-capacitor measurement structure

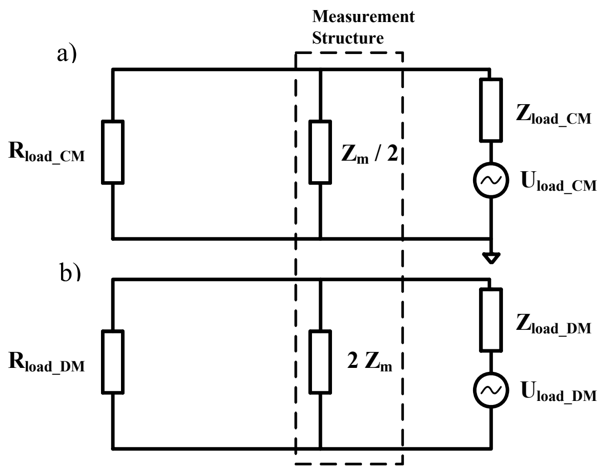


Figure 3. Common- (a) and differential-mode (b) equivalent circuit with separated measurement structure

R_{load_DM} is equivalent to 100 Ω, R_{load_CM} to 25 Ω, resulting out of the two 50 Ω LISN impedances as derived out of figure 2. With the obtained common- and differential-mode values, with and without measurement structure, the input impedance can be derived:

$$Z_{load\_CM} = \frac{a_{CM} - 1}{\frac{1}{R_{load\_CM}} - \frac{a_{CM}}{(R_{load\_CM} \,||\, (Z_m/2))}} \tag{3}$$

$$Z_{load\_DM} = \frac{a_{DM} - 1}{\frac{1}{R_{load\_DM}} - \frac{a_{DM}}{(R_{load\_DM} \,||\, (2Z_m))}} \tag{4}$$

with the voltage factor a_{CM} and a_{DM}:

$$a_{CM/DM} = \frac{V_{CM/DM} \text{ with measurement structure}}{V_{CM/DM} \text{ without measurement structure}} \tag{5}$$

The exact complex values for $Z_m(f)$ are generated with the help of an impedance analyzer (HP4294) in the frequency range from 0.15 – 110 MHz. As a first approximation R_{load_DM} and R_{load_CM} can be treat as real values. The remaining variables in the equations (3)-(5) are represented through complex values.

Well-established EMI measurement receivers and spectrum analyzers can only support amplitude information about the measured common- and differential-mode noise signals; phase information is getting lost. The only possible way to find phase information would be to provide a time domain measurement with a following Fourier- Transform. However, due to the two needed setups, with and without measurement structure, it is difficult to find the exact same time-offset position for the signals. A time-shift would generate a phase-shift in the frequency domain and thus lead to inaccurate phase information. Even with the possibility to use an internal trigger signal out of the DUT, small time shifts or a jitter of the noise signal can cause a significant phase distortion. Only for simulation purposes it is possible to obtain the correct phase information due to the use of parallel simulations.

If only amplitude information is available, a worst case estimation can be derived if every possible phase angle of the voltage factor $a_{CM/DM}$ is considered. The voltage factor $a_{CM/DM}$ is determined from the division of the two measured voltages with and without measurement structure, in the following called v_{1_CM}, v_{1_DM}, v_{2_CM}, and v_{2_DM}, or simplified v_1 and v_2. Thus equation (5) can be written as:

$$\frac{v_1 e^{j\beta_1}}{v_2 e^{j\beta_2}} = a e^{j\beta_3} \tag{6}$$

Actually β_3 is mathematically derived out of $\beta_1 - \beta_2$, however, as both phase angles are unknown, β_3 has to be assumed to be within the range of $0..2\pi$. Thus, it is possible to find multiple solutions and at least maximum and minimum values for the input impedance Z_{load_DM} and Z_{load_CM}.

With the derived input impedance it is possible to estimate the available filter attenuation for a given EMI filter. For simple filter structures, as shown in table I, it is possible to measure the filter impedance directly with the help of an impedance analyzer. For complex filter structures, a four port scattering-parameter measurement can determine the admittance and impedance matrix of the filter [7], [8].

IV. Experimental Setup

For the experimental setup a simple step-down switching regulator (buck converter) from Linear Technologies LT1375 was used as device under test. The switching frequency of the device is set to 500 kHz. The setup (PCB) was built up ignoring any EMC- rules, so the converter acts as a good noise generator for conducted emissions.

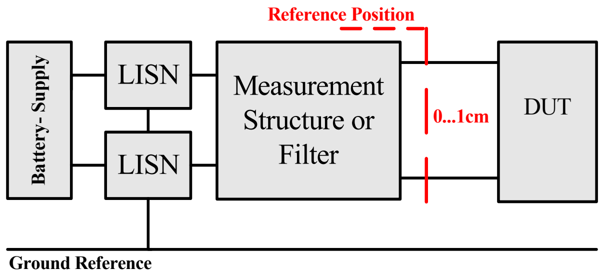


Figure 4. Experimental setup with the DUT, measurement structure, LISN and battery supply

The buck-converter is placed 5 cm above the reference ground plane.

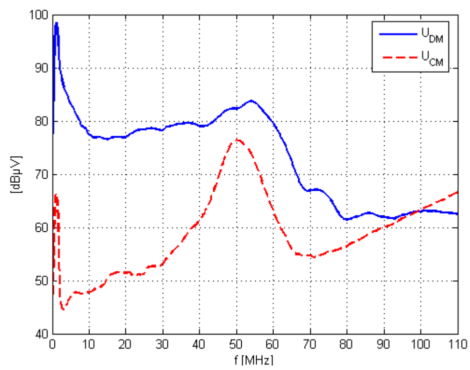


Figure 5. Measured common- and differential-mode noise voltage without filter / measurement structure

To receive a smooth noise graph for common- and differential-mode disturbances, which can be easily processed within the algorithm, the scanning receiver is other than in CISPR25 defined set to 1 MHz bandwidth.

Otherwise a shift at narrowband peaks can cause a significant error during the evaluation of equation (3) and (4). A shift of narrowband peaks can occur due to the non stable operation of the DUT.

Figure 5 shows the measured common- and differential-mode noise voltages of the buck-converter. The differential-mode is hereby the dominant disturbing noise source of the DUT. To determine the input impedance of the system, the measurement structure, including two 1.5 µF capacitors as Y-structure, is connected to the DUT and the measurements for common- and differential-mode are repeated. The input impedance can now be calculated with equation (3) and (4) in respect to section III B.

V. INFLUENCE OF THE LEAD LENGTH TO THE INPUT IMPEDANCE

The first test of the procedure is to determine the influence of the lead length, which connects the DUT with the measurement structure and the final filter. First, only the differential-mode is considered and thus the measurement structure is simplified to an X- capacitor. A 1.5µF capacitor is used to obtain the differential input impedance Z_{load_DM}. The lead length to the measurement structure is varied between 0 and 1 cm. Zero cm corresponds to a direct assembly of the filter capacitor to the PCB of the DUT.

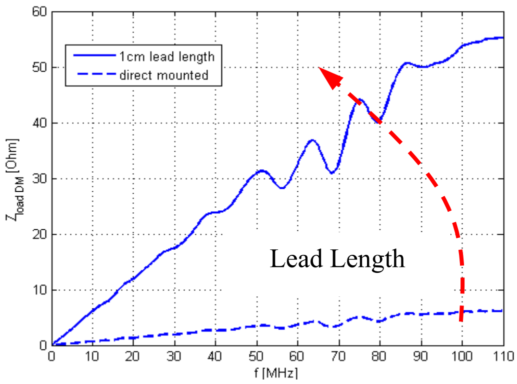


Figure 6. Differential-mode input impedance for different lead length to the measurement structure

As seen in figure 6, the lead length of the connector shows a significant influence on the differential input impedance. This length represents an offset of the reference position in figure 4, from which the device is characterized. The input characteristic shows a pure inductive behavior over the frequency range which is affirmed by the reduction of the inductance by changing the reference position and thus decreasing the lead inductance.

The voltage factor a_{DM} is assumed to be real, whereby the phase angle β_3 can be neglected. If a minimum and maximum estimation (as described in equation 6) is considered, the input impedance behavior stays inductive; however, with much higher and lower values in amplitude.

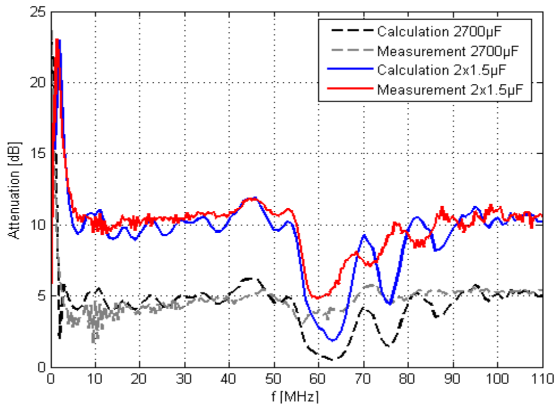


Figure 7. Differential-mode attenuation for different X-capacitors. Calculation and measurement results.

To test the setup and the assumed simplifications, two different X-capacitors are soldered to the input connector. One additional bulk-capacitor with 2700 µF and two 1.5 µF capacitors in parallel connection. The test concerns to the measured input impedance named as direct mounted, compared to figure 6. As seen in figure 7, the attenuation of both filter elements can be predicted with the obtained input impedance over the whole frequency range. Especially the peak attenuation around 1-3 MHz corresponds to the calculation results.

The filter attenuation A_{filter} is hereby defined for common- and differential-mode as:

$$A_{filter}[dB] = V_{without\_filter}[dB] - V_{with\_filter}[dB] \qquad (7)$$

VI. CONSIDERING COMMON- AND DIFFERENTIAL-MODE

Normally it is not possible to mount a whole filter directly to the connector. Thus the filter structure is assembled to an additional PCB with 1 cm leads to the DUT, and with the input impedance shown in figure 6. For the measurement structure a Y-capacitor with two 1.5 µF capacitors in series connection is used to determine the input impedance for common- and differential-mode. As for the differential-mode, the common-mode input impedance shows inductive behavior. The results in figure 8 are achieved for a filter with two 100 nF capacitors in series connection (Y-structure). The maximum deviation between the calculated and measured common- and differential-mode attenuation is less than 5 dB over the whole frequency range. With the help of the information about the input impedance it is possible to calculate the attenuation of arbitrary X- and Y-structures.

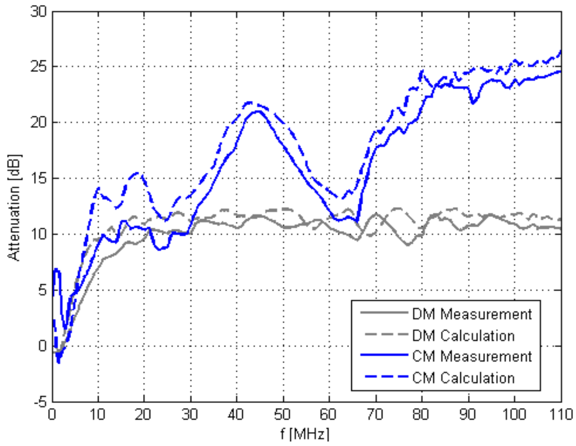


Figure 8. Measured and predicted common- and differential-mode attenuation

To obtain an accurate calculation of the estimated attenuation it is necessary to know the behavior of the filter elements over the frequency range, and the impedance matrix [$\underline{Z}_{filter}$(f)]. For a very simple estimation the parasitic elements can be determined out of the data sheet. However, a simple description of the elements, e.g. for a capacitor with ESL (equivalent series inductance) and ESR (equivalent series resistance), is not accurate enough. Only a measurement of the impedance of the elements with an impedance analyzer will result in more accurate solutions. Special care should be paid to the PCB routing, as well as the element placement as shown in [9].

The track length on a PCB to the filter elements can have a significant impact to the filter attenuation. Additional track inductance causes a significant decrease of the common- and differential-mode attenuation. With the help of PCB simulation programs it is possible to predict the leads inductance to the filter attenuation as shown in [10].

The procedure is tested for multiple capacitor structures to show the influence of additional parasitic inductance and impedance (ESL, ESR) to the attenuation.

VII. Limits of Common and Differential Mode Separation

In general, the common- and differential-mode decomposition assumes the equivalent circuits stated in figure 3. Both circuits are represented as independent of each other, so there is no possibility of interaction between common- and differential-mode. The impact of different filter structures to the noise modes is shown in table I. In respect to the equivalent circuits from figure 3, there is no possibility for an X-structure to influence common-mode noise, because both power lines are set to the same voltage level for common-mode incitation. In reality, a simple parallel connected X-capacitor as used in figure 7, generates an impact to the common-mode noise voltage. Figure 9 shows the predicted and measured common- and differential-mode attenuation for a 33 µF capacitor. The calculated differential-mode attenuation shows a maximum deviation of 2 dB, compared to the measurement result from 2 – 110 MHz. Up to 2 MHz the X-capacitor forces a common-mode attenuation up to 12 dB. This is also the range within the differential-mode prediction fails. The maximum deviation between the measured and simulated filter attenuation should not exceed more than 5 dB. On the basis of the equivalent circuit for common-mode, the calculation result shows no attenuation and stays zero over the whole frequency range.

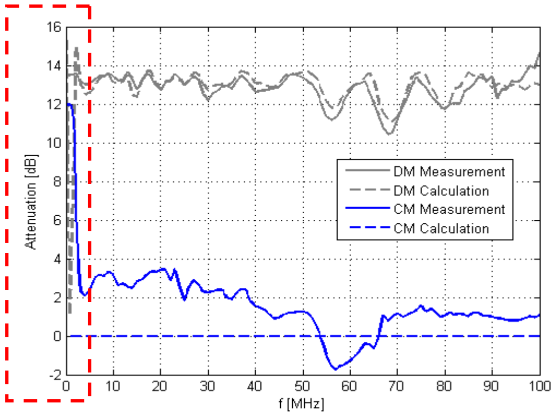


Figure 9. Measured and simulated common- and differential-mode attenuation of an X-capacitor (33µF)

More significant deviations are present if asymmetric filter structures are considered. The symmetry is hereby defined as the symmetry based to the reference ground. A simple asymmetric filter can be built with an inductor in one power line of the DUT. Based on the equivalent circuits a series inductor will create a significant differential– to common-mode noise conversion.

To describe the whole system from figure 3, four independent variables are necessary. Up to now only Z_{load_CM} and Z_{load_DM} are considered. Essentially there are two more, namely U_{load_CM} and U_{load_DM}, which can also be extracted from the equivalent circuits in figure 3. Again, the phase angle of the voltages can only be guessed and a worst case approximation can be made to estimate the occurring mode conversions. Figure 10 shows the measured and simulated attenuation results for a 2.7 µH inductor. The differential-mode prediction is comparable to the measurement results up to 40 MHz. However the common-mode model is only valid up to 10 MHz. Especially the negative attenuation respectively amplification of the noise level, in a frequency range from 50 – 90 MHz has to be considered during the filter development process.

It is therefore not advisable to use series inductors as possible filter elements in respect of common- and differential-mode separation.

The same results can be achieved by applying a spice simulation to review the obtained results.

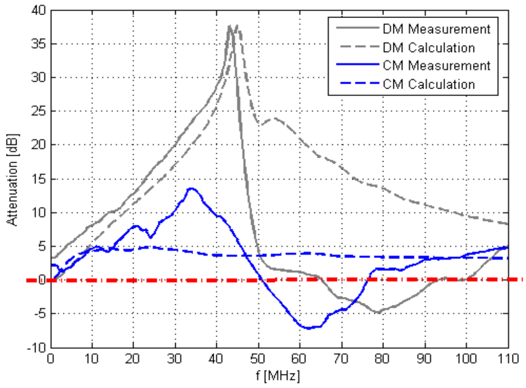


Figure 10. Measured and simulated common- and differential-mode attenuation of a series inductor (2,7µH)

One more limiting reason represents the resonance frequency of the measurement structure. The measurement capacitors should be chosen with a resonance frequency outside of the considered frequency range. The resonance frequency of the above used capacitors, as measurement structure, is around 500 kHz.

As shown, the widely-used common- and differential-mode equivalent circuits can not describe the general behavior of an arbitrary DUT. Especially if only the amplitude information of the disturbing mode sources are available. But why?

The equivalent circuits in figure 3 are based on the four independent parameters Z_{load_CM}, Z_{load_DM}, U_{load_CM} and U_{load_DM}. However, in general the DUT represents an active two port circuit. In respect to Thévenin's law, every arbitrary active two port can be described by a two port impedance matrix and two active sources. To describe the overall DUT, six independent parameters are necessary in equation (7).

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \times \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} + \begin{bmatrix} u_{q1} \\ u_{q2} \end{bmatrix} \qquad (7)$$

Four parameters for the impedance matrix [Z] and two parameters for the active sources [Uq], where all parameters are representing complex numbers over the frequency. Unfortunately, the phase angle is essential to extract all parameters whereby the same problem arises as described for common- and differential-mode measurements. Nevertheless the full description is a useful technique to describe arbitrary network simulations. Time intensive transient network simulations can be characterized within the frequency range for the following filter development process. The parameters can be extracted with the help of three simulations, calculating each two parameters. If the impedance $[Z_{filter}]$ or admittance $[Y_{filter}]$ matrix of the filter element is known, the filter attenuation can be predicted in respect to the line voltages as well as the common- and differential-mode attenuation.

VIII. Conclusions

With the help of common- and differential-mode separation it is possible to evaluate the distribution of the noise modes over the frequency. Thus, it is possible to choose the filter elements in respect to the dominant noise mode. With the help of two auxiliary measurements it is also possible to determine the common- and differential-mode input impedance of the system and to predict the resulting filter attenuation for symmetric filter structures. Special care should be taken when using elements which can generate mode conversions. The well known equivalent circuits can not cope with mode conversions due to their independent consideration. Series inductors are especially responsible for mode conversions and can cause a negative attenuation in the worst case.

Although it is not possible to describe the system completely with the common- and differential-mode decomposition it is a useful approximation during the filter development process.

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