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Electromagnetic Interference, Microphones and Cables

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ABSTRACT

All electronic devices in the audio chain are susceptible to external electromagnetic interference. Interfering signals are moving higher and higher in the radio frequency spectrum, the current must important disturbing element being cell phones.

Standardized measurement systems are available. Although mentioned in the relevant microphone standards, data is seldom published. Actual measurements on different microphones, cables and wiring topologies shall be presented and discussed.

1. INTRODUCTION

All electronic devices in the audio chain are to some extent susceptible to external interference. Testing audio devices for faults, defects or interferences is certainly one of the most annoying tasks for any engineer working in development. The end-user on the other hand will gladly prefer equipment that has been tested thoroughly for all foreseeable and unforeseeable eventualities.

The experienced user will have seen, or rather: heard, all sorts of interferences and disturbances in his professional life: hum & buzz, frequency dependant signal-loss, interference from light systems, radio, TV, or cell phones. These disturbances, how they can be measured, and avoided, shall be discussed.

Current legislation, especially the European directive on EMC (electromagnetic compatibility), has led to standardized methods for measuring the influence of radio frequency signals on audio devices. EMC measuring systems can be quite costly, but the results justify the expense. The results are reproducible, in contrast to empirical "on-location" findings, or earlier methods used in laboratories.

2. CONNECTIONS AND IMPEDANCES

In all but the most "affordable", meaning cheap, equipment, the connection between microphone and the following amplifier will be balanced. Microphone cables will thus hold at least two signal conductors, plus a shield, used for grounding, and phantom-voltage return in the case of phantom powered microphones [1, chapter 7.4]. Balanced in this case does not necessarily imply signal symmetry, i.e. that both signal wires transmit the audio signal in opposite polarity and with equal amplitude. The important factor for rejection and attenuation of disturbances is that the impedances of the two signal lines be identical.

The principle of "voltage matching" is generally used nowadays for microphones. The microphone output impedance (source impedance) is chosen as low as possible, the amplifier's input impedance (load impedance) as high as possible. A minimum ratio of 1:5 should be maintained in all situations [2][1]. For a lower ratio, the amplifier puts a higher load on the microphone, which might then not be able to fulfill all specifications. The main effects will be changes in frequency response and/or maximum output capabilities as well as distortion values.

Preferred values for microphones and amplifiers are given in [1, Table4]: $R_{M,Sum}$ =200 ohms maximum output impedance for microphones, R_L=1kohm minimum input impedance for amplifiers.

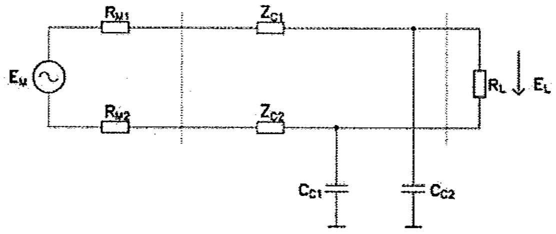

Figure 1 Model of microphone, cable and amplifier

The microphone can be modelled as a signal generator, see fig. 1, situated between the two signal wires, plus resistors R_{M1}, R_{M2} for the output impedance. For electronically balanced output circuitry, the output impedance will be mostly frequency independent. For transformer balanced outputs, the impedance rises towards lower frequencies. In both cases, data sheets should state the "worst-case" value, i.e. the maximum impedance arising in the microphone's working frequency range. For the purpose of this paper, purely resistive impedances are mostly sufficient to model the microphone's behaviour. Methods for measuring microphone output impedance are described in [2, chapter 9]. Likewise, the following amplifier is modelled as a resistor R_L for the input impedance. The values given in the data sheet should hopefully state the minimal input resistance, over the whole working frequency range. Here as well, resistive impedance serves to model the amplifier input.

For most situations, a further simplified schematic can be used; lumping the balanced impedances of positive and negative signal conductors into one, we obtain a very simple, unbalanced schematic (figure 2).

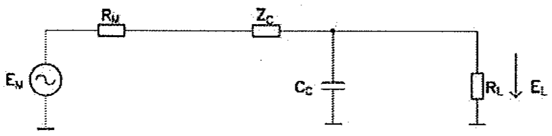

Figure 2 Simplified model of microphone, cable and amplifier

With short cables, both Z_C and C_C can be neglected. Then the voltage E_L at the amplifier input will be

$$E_L = E_M * R_L / (R_L + R_M) \qquad (1)$$

The influence of impedance matching and mismatching can easily be demonstrated with frequency responses of microphones. The condenser microphone in figure 3a has a basically resistive output impedance R_M = 50ohms. Loading the microphone with R_L = 1kohm makes next to no difference compared to a no-load situation. The resulting sensitivity difference is 0.4 dB; the curves in figure 3a lie on top of each other. The dynamic microphone in figure 3b has a rated impedance of R_M=200ohms. With R_L = 1kOhm we find the expected loss in sensitivity of 1.6 dB. In reality, the microphone's moving coil construction produces higher (mostly inductive) impedance R_M at low frequencies. Accordingly, we find some 2 dB additional low frequency roll-off at R_L = 1kohm.

For the sound engineer this means that the sound of dynamic microphones (and to some extent all transformer-output microphones) depends on the input

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[1] With a 1:5 ratio between microphone and amplifier impedances, a signal attenuation of 1.6 dB maximum is produced, compared to the no-load situation.

impedance of the following amplifier; while low impedance, transformerless condenser microphones produce a more constant sound, irrespective of the load.

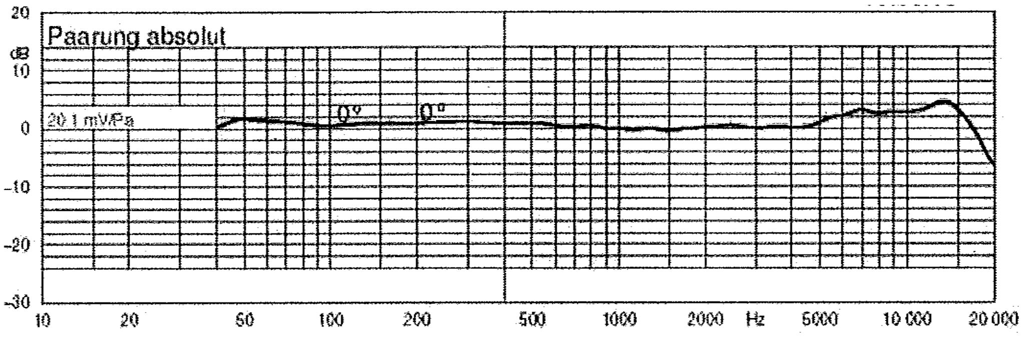

Figure 3a: Frequency response of condenser microphone #3(upper graph), with no load (upper curve), and with R_L = 1kohm (lower curve)

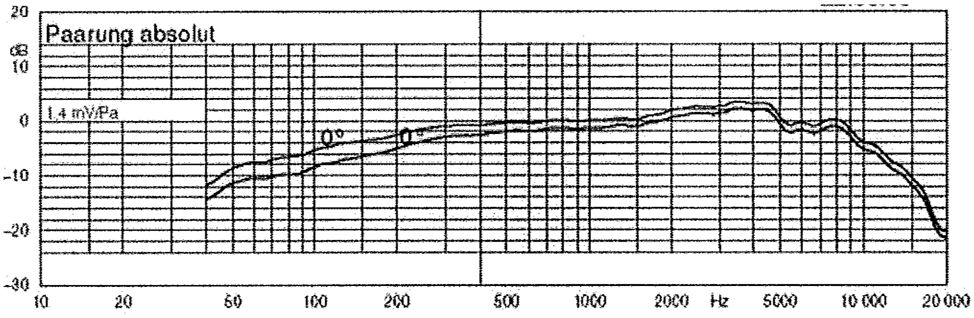

Figure 3b: Frequency response of dynamic microphone #4, no load (upper curve), with R_L = 1kohm (lower curve)

The cable then, is the necessary "evil" to connect source and load. Especially with longer cable lengths, resistive, inductive and capacitive impedances come into play. The resistive component of wires and shield is easily measured. High quality cables have e.g. a resistance of 100 ohms/km, which makes it clear that in most situations, and even with long cable runs, the resistive influence can be neglected.

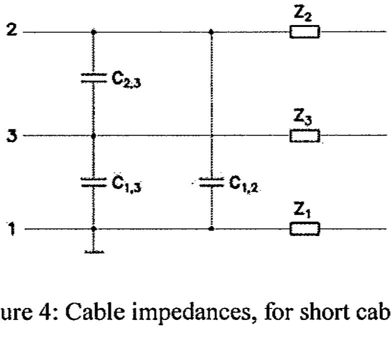

Figure 4: Cable impedances, for short cables.

For capacitance measurements all inter-wire capacitances plus the wire-to-shield capacitances combine. Typically one measures the summed capacitances, and $C_{1,2}$, $C_{1,3}$, $C_{2,3}$ are the result of calculations.

For short cable runs the model consists of small value in-line resistive impedances Z_1, Z_2, Z_3 in signal wires and shield, and capacitances $C_{1,2}$, $C_{1,3}$, $C_{2,3}$ between wires and shield.

The effect of cable capacitance can best be seen with a wide-band measurement of a condenser microphone circuit. This specific microphone has a very low output impedance of 50 ohms. The no-load frequency response is remarkably flat. The beginning LF roll-off at 20 Hz is the result of the phantom power blocking capacitors in the microphone output. This roll-off is accordingly increased, when an amplifier with $R_L = 600$ ohms input impedance is connected. Simulating a VERY long cable with a load of C_{SUM} = 47nF produces a still rather harmless HF roll-off at 40 kHz (-3 dB).

Note: 47nF corresponds to 170 ohms capacitive reactance at 20 kHz, roughly 3 times the value of the microphone's output impedance. The results confirm the validity of [1, chapter "Interconnections", 4.1.1.5], where it is stated that "the capacitive reactance should exceed 3 times the source impedance at the highest frequency of interest. This ensures less than approximately 1 dB loss at the highest frequency of interest".

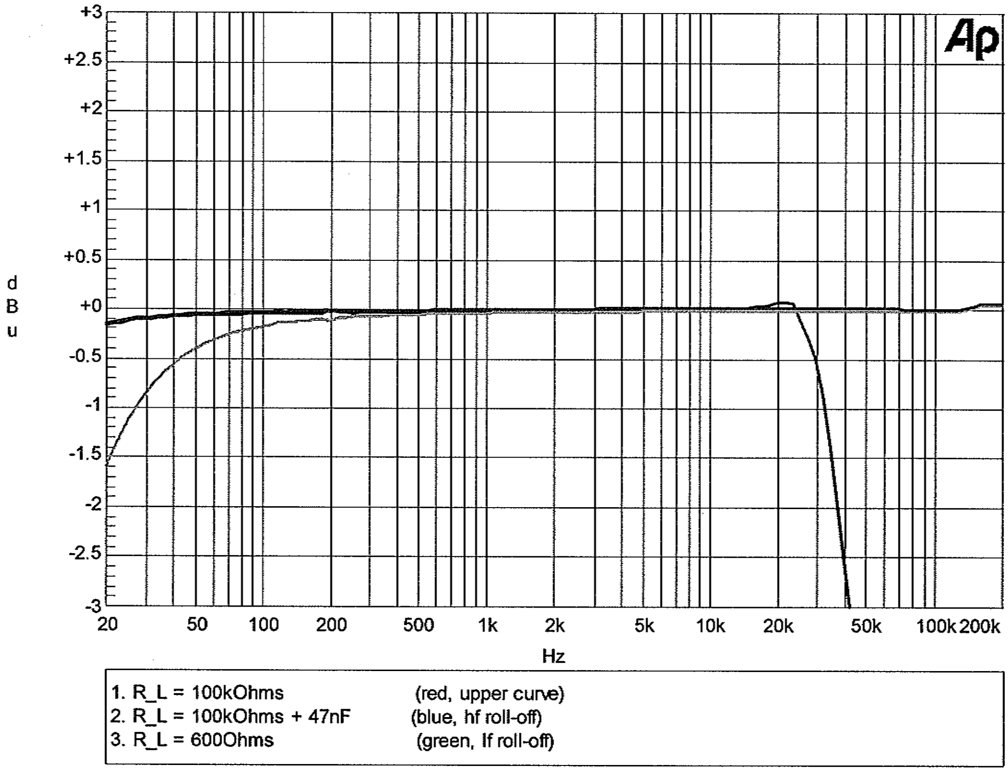

Figure 5: Effect of 1) simulated cable capacitance and 2) resistive load on microphone response

With "real" cables, further effects come into play. Figure 6 shows the results with 100m of high-quality "analog" cable #1; figure 7 with 100m of similarly high-quality "digital" 110ohms cable #2.

In a no-load situation, the cable's inductance can lead to some 2.5 dB resonance in the 100...200 kHz range, especially with cable #2. Otherwise, the frequency response is unaffected.

Adding an amplifier with R_L = 600 ohms input impedance, this ultrasonic resonance is slightly damped. The LF roll-off seen already in figure 5 once again results from the microphone's phantom-blocking capacitors. As a final effect, the cable's resistance produces an over-all attenuation of the signal by roughly 0.2 dB in the case of cable #1, 0.3 dB with cable #3. Summing up, one might judge this specific microphone circuit to be rather insensitive to the typical resistive, reactive and capacitive loads produced by cables in real-life situations.

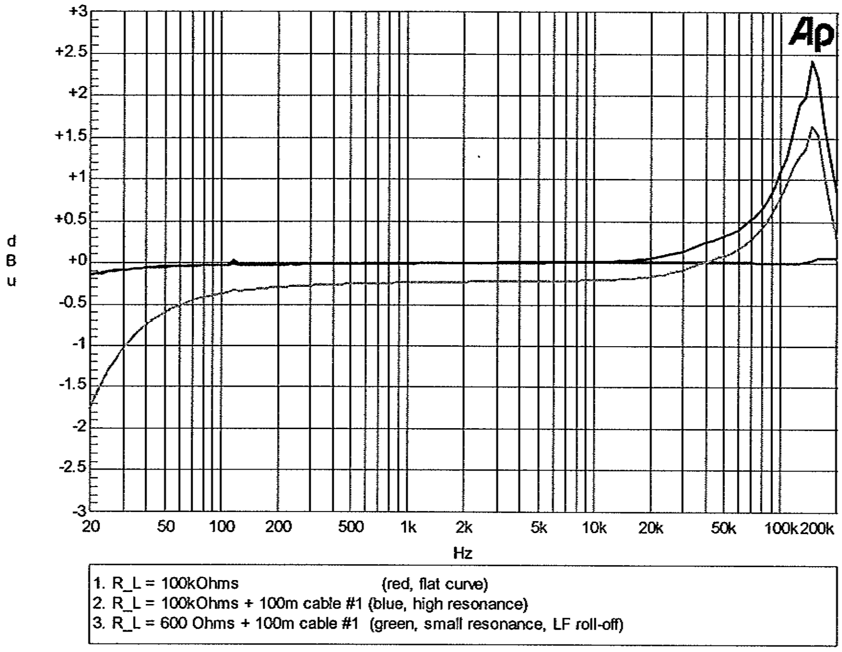

Figure 6: Effect of cable #1 on microphone response

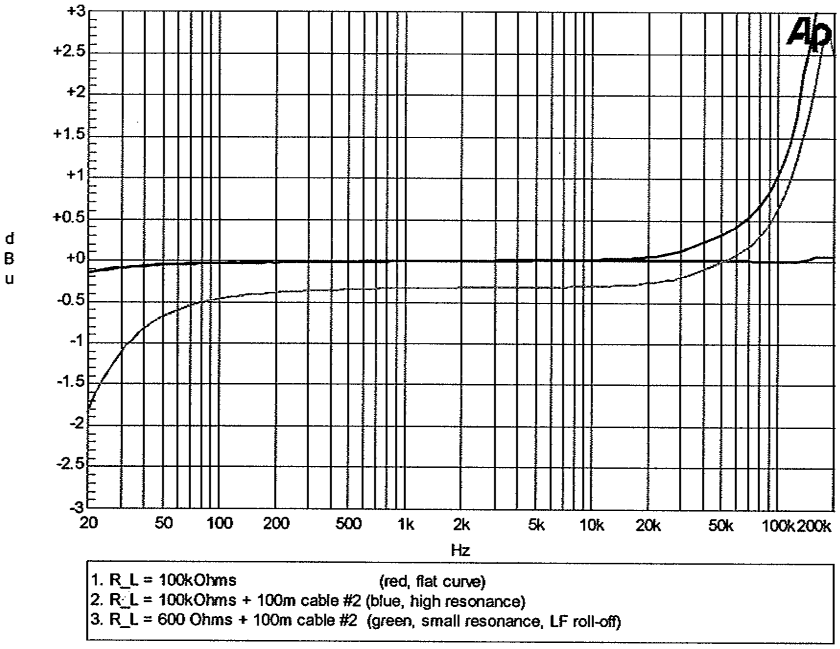

Figure 7: Effect of cable #2 on microphone response

High load impedances can produce further effects. The output stage of any microphone will only be able to drive a certain load. With a lower load impedance R_L than the minimum load stated in the data sheet, a microphone might not be able to fulfill all specifications. Especially with high level output signals produced by high sound pressure levels, low load impedances will place a heavy burden on the output stage. In effect, the maximum output level of condenser microphones, for a certain maximum amount of distortion (typically 0.5% THD) depends on the load impedance. That there are differences in circuit design is clearly shown in figure 8. Microphone #1 is perfectly capable of driving all loads $R_L \geq 1$kohm, as specified in [1]. Even for loads down to 300 ohms the microphone's maximum signal handling capability is only reduced by 3 dB. In contrast, the circuit of microphone #2 clearly prefers very high load impedances. The manufacturer accordingly specifies a minimum load of R_L=2.5kohm; while operating the microphone at the standard minimum load of R_L=1kohm already reduces the microphone's headroom by 6 dB!

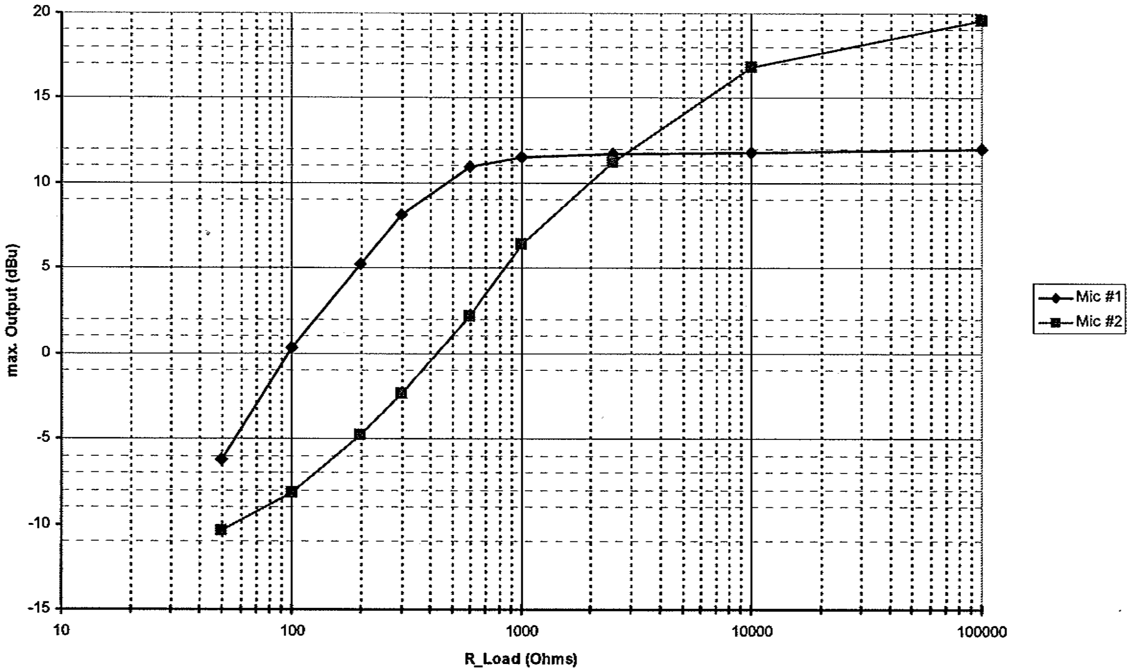

Figure 8: Max SPL of 2 condenser microphones over load impedance R_L

These unwanted limiting effects have to clear to the user, especially when using low input impedance amplifiers; or, when a microphone is used to drive 2 or more inputs in parallel, as with passive splitters or Y-split cables, where the parallel impedances can combine to a very low resistive value.

3. HUM & BUZZ

The most common interfering noise in larger scale audio systems is certainly hum & buzz, caused by ground loops. For ground loops to appear, the audio system has to be grounded at two or multiple locations, causing shield current to flow along the cable from one device to the other. Comprehensive papers on this topic are found in [3], [4].

Thankfully, microphones are seldom involved in these cases. The vast majority of microphones have a metal, conductive housing with the purpose of providing a complete Faraday shield against any sort of interference. Still, most clamps or mounts provide electrical insulation against house ground through one or more of the following mechanisms:

- clamps at least partly made of non-metal materials,
- rubber parts / feet integrated in the stands
- non-conductive floor / carpet.

Only in rare cases, as e.g. a microphone held with a metal gooseneck on a metal podium connected to house ground will we find a situation where a ground loop problem involving the microphone itself may arise. Breaking up such a ground loop can be achieved quite simply by introducing some insulating material anywhere in this ground connection.

4. MAGNETIC INTERFERENCE

Methods for measuring the sensitivity of microphones to external magnetic fields are described in [2, chapter 18.2]. Especially microphones of the moving coil type are prone to this type of interference, stemming from lighting systems, power transformers, motors, etc in the vicinity of the microphone. High-quality dynamic microphones thus include a hum compensation coil situated close to the moving coil. Condenser microphones are in general not overly susceptible to magnetic fields, and accordingly the sensitivity of such microphones to external magnetic fields is seldom stated in data sheets. To keep the influence of magnetic fields small, the general rule of "keeping the wires together" is essential. Thus, cable leads should be kept as short as possible, and the signal leads of balanced lines twisted around each other as closely as possible. This does include the few centimetres of free wire length inside XLR connectors.

5. ELECTROSTATIC DISCHARGE

Without further going into details, the topic of electrostatic discharge (ESD) is treated in [2, chapter 18.7], referencing [5]. In most cases, the shielding & grounding topologies necessary to avoid all other disturbances will be perfectly sufficient to minimize the effects of ESD. For information, it might be noted that ESD tests apply voltage peaks of 4kV and 8kV to the device under test.

6. ELECTROMAGNETIC INTERFERENCE

6.1. The interference mechanism

One might ask why signals in the 100kHz-to-GigaHz range do cause audible disturbances at all. The mechanism generally is that these RF signals enter the circuitry, and are demodulated at some non-linear electrical component, generally semi-conductors. As semi-conductors only work linearly over a finite amplitude & frequency range, excessive RF interference will cause audible artefacts. With the exception of purely passive devices like moving coil & ribbon microphones, all microphones and amplifiers can potentially demodulate RF signals.

Now, where & how do RF signals enter the signal chain? As has been said, the microphone housing generally has good shielding properties regarding electromagnetic interference directly entering the housing and thus the circuit. The same should hopefully hold true in the case of amplifiers; but here we often find semi-professional or customer designs with plastic housings or only incomplete shielding. In such a case often not much can be done except exchanging the device for a properly designed one.

For the further discussion, let us assume that microphone and amplifier housing do provide good shielding. This leaves the cable and connectors as the main entry port for RF signals into the audio signal chain.

The RF signal enters the cable shield. Zero cable impedance and zero resistance connection of a 100% effective cable shield to ground would drain a large portion of the RF signal. Of course, in reality none of these requirements can be fulfilled. Real cables will thus act as antennas, and depending on shield technique (spiral counter-wound, braided or foil shield), insulating material, wave length, impedance, balance, etc. couple the RF signal into the audio signal wires, consequently reaching both microphone output and amplifier input connectors.

A further, critical point of entry into the system is the connector, which in most cases will be of the XLR-type. Ever since the beginnings of radio and TV broadcast technology the necessity of shielded connectors is known. Recent debates on proper connection of cable shields to connector shells and microphone & amplifier housing [3] have led to the publication of a new AES standard [6], partly based on the field test findings in [7]. There it is said for microphones [6, chapter 4.4] that "the designated shield contact and the shell of the microphone connector shall have a direct-current connection to the shielding of the microphone via the lowest impedance path possible". With existing XLR connectors this means that Pin1 (designated shield contact) should be connected with Pin0 (e.g. solder lug, connecting to the connector shell), see figure 9. One could argue that in most microphones, Pin1 would be internally connected to the mic housing anyway, in order to ground the housing; and, that in most cases, the metal microphone body would then implicitly ground the connector shield as well. But practical tests do show that between mic body and XLR shell there is no reliable low impedance connection and that, especially with combining XLR connectors from different manufacturers, the contact resistance R_X lies between zero and open circuit. In order to keep the signal wires properly shielded for the length of the XLR connector, internal connection of Pin0 to Pin1 is necessary. This is in contrast to the wiring found in many commercially available cables, which leave the Pin0-Pin1 connection open in order to avoid ground loops. Alternatively, effective new solutions do exist, with XLR connectors with separate internal shielding mechanism [8].

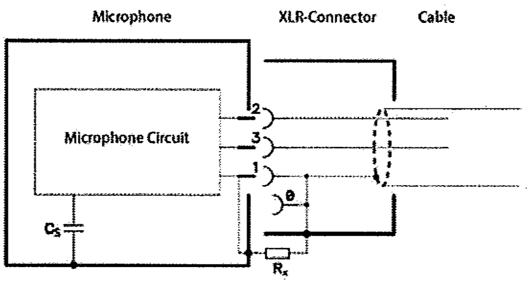

Figure 9: Microphone, XLR-connector and cable connections.

Still, even with perfect connectors, a certain amount of RF signal will still enter the microphone (and amplifier) housing. There, it lies in the responsibility of the microphone designer to implement any of the known mechanisms of either shielding off the internal propagation of the RF signal, or attenuating and bypassing the effects in the vicinity of potential demodulators.

6.2. Measurement setup

How is EMC then tested? Real-life experiments with TV and radio stations or lab tests, with cell phones and handheld FM transceivers as in [7] do give relevant impressions of a device's immunity against EMI, as can be confirmed by the author. Albeit these tests only cover a limited frequency range of interferences. With the current EU directives on EMC, and the large number of standards implemented since then, a framework has been implemented for performing wide-range measurements [2, chapter 18.6], referencing [9]. A typical modern lab setup will hold a so-called GTEM [Gigahertz Transversal Electromagnetic] test cell. In the GTEM cell used in the following, measurements can be performed in one go, in the frequency range from 30 MHz - 2.7 GHz, covering most of today's broadcast spectrum.

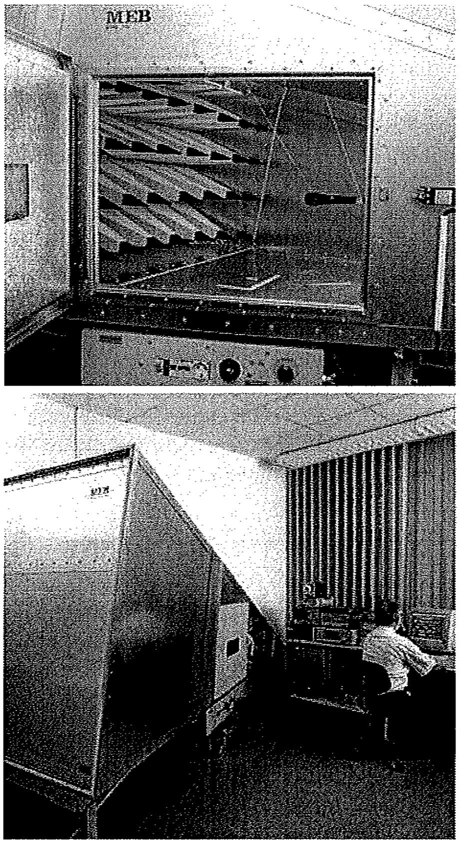

Figure 10: GTEM [Gigahertz Transversal Electromagnetic] test cell.

As stated in [2, chapter 18.6] for measuring microphones, the following test parameters should be set: RF source with a) 1kHz, 30% amplitude modulation, and b) 1 kHz, 22 kHz frequency modulation. Field strength shall be 10 V/m. The microphone output is measured as CCIR-weighted noise, quasi-peak. It might be noted that with 10 V/m the highest field strength class ("heavy industrial and environments close to broadcast transmitters") of the possible classifications in [10] has been chosen for the microphone standard [2].

6.3. Measurements

The following measurements were all performed in the above mentioned GTEM cell. Some parameters were changed over the years, i.e. field strength varied between 1, 3, and 10 V/m; amplitude modulation factor was 80% (earlier) and 30% (current measurements). It has to be noted that y-axis is in mV. The horizontal line is the actual CCIR-weighted noise floor of the microphone!

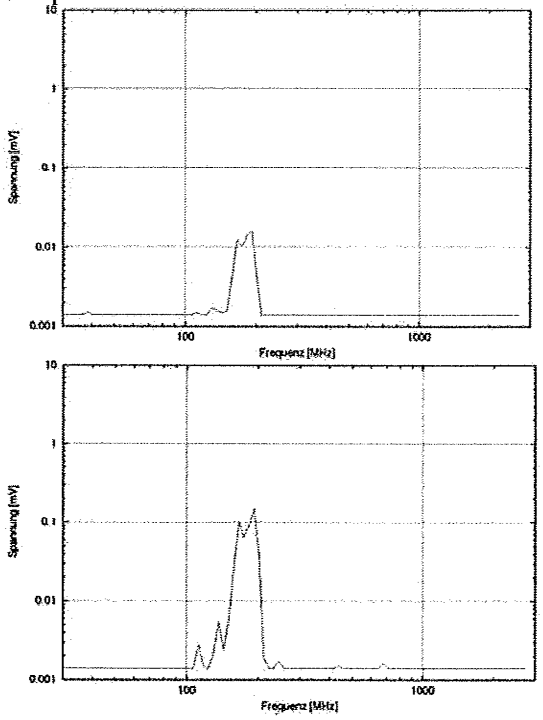

Figure 11: EMI of condenser microphone #3, at 1 V/m and 3 V/m field strength, 80% AM

Demodulation is due to non-linearities. That there is some linearity even in non-linear behaviour is shown in figure 11. 10 dB higher field strength leads to EMI increased by 20 dB, following the quadratic rule.

EMI depends on orientation of the microphone relative to the electromagnetic field. Consequently, a complete set of measurements consists of a minimum of 3 measurements to find the worst-case orientation of the microphone, see figure 12. (Note: measurement amplified by 10 dB additionally)

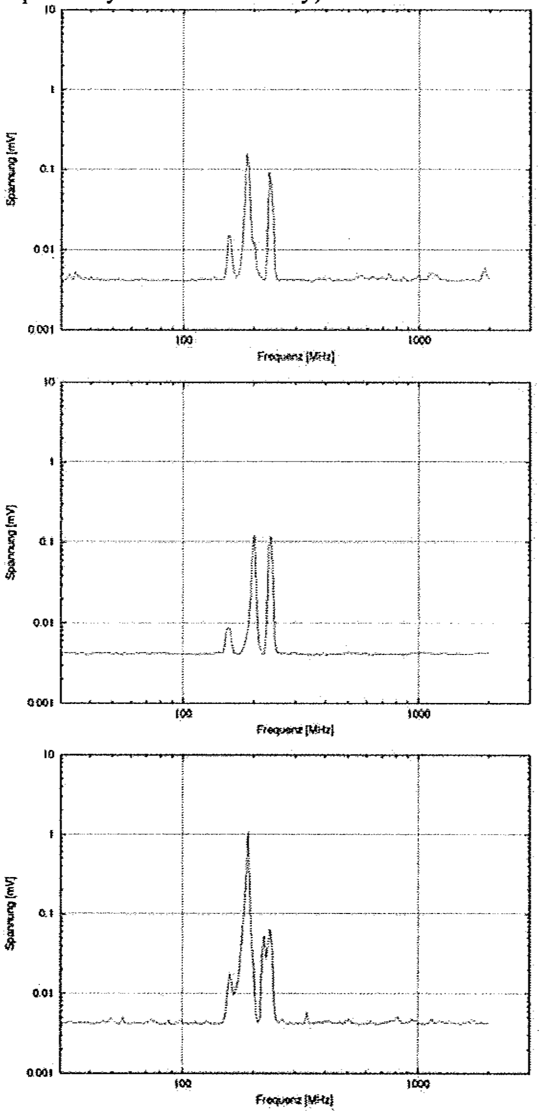

Figure 12: EMI of an earlier version of condenser microphone #3, at 3 V/m field strength, 80% AM, in z-, y-, x-direction (amplified 10 dB)

With older microphones, one sometimes finds that the circuit and mechanical construction make it extremely difficult to achieve improved EM-immunity. But in some cases, comparatively small modifications in the circuit lead to large changes, see figure 13. In this special case, it was not really the microphone's problem, but the user's plug-on wireless transmitter directly injecting unfiltered HF backwards into microphone.

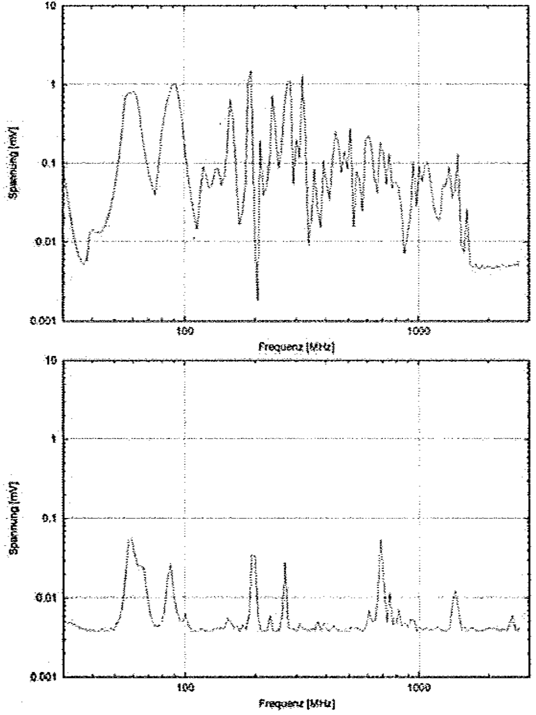

Figure 13: EMI of an older condenser microphone #5, at 10 V/m field strength, 80% AM, before and after the modification.

Finally, figure 14 shows measurements with 3 different cable connector topologies (out of 11 different cable / connector combinations measured), as discussed in chapter 6a. As the circuit and construction of microphone #6 was already designed with attention to EMI, the results show that none of these topologies will lead to any audible interference in the vast majority of applications. With this very immune microphone, clearly the setup with no Pin0-Pin1 connection (figure 14b) still shows the worst situation, as here the XLR shell does <u>not</u> shield the open wire ends. With Pin0-Pin1 connection, as with the special connector, the situation is improved but without a clear winner over the complete frequency range. As in the case of microphone #6, the author found that the effect of connector topologies does vary with circuit & grounding topologies inside the microphone, which makes it very difficult to give "one rule to solve all problems".

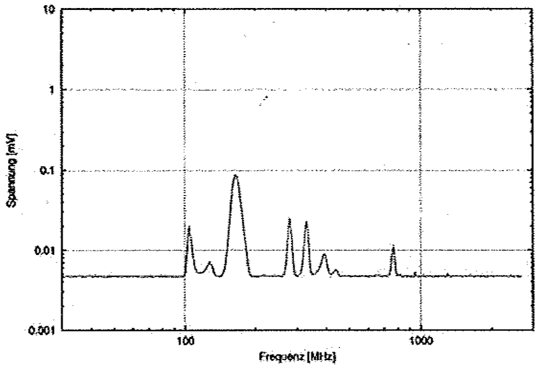

Figure 14a, Pin0-Pin1 connected on XLR3F side

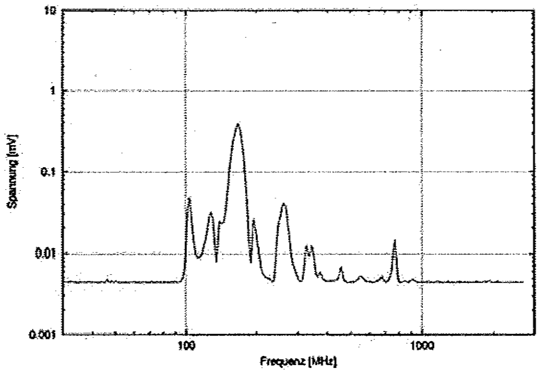

Figure 14b, no Pin0-Pin1 connection

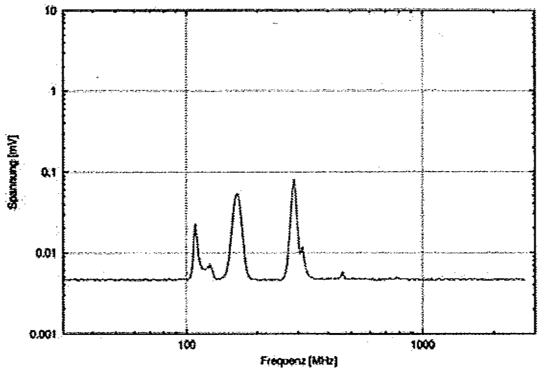

Figure 14c, with special XCC-connector following [8]

Figure 14, Microphone #6, different connector topologies, 10V/m, 30% AM, (amplified 10 dB)

What can be said is that the open-shell topology, as in figure 14b, in most cases proved to be a bad or worst case, confirming earlier empirical findings by colleagues, the author, and the field test results in [7]. The limits of what is achieved in current designs, is shown in Figure 15.

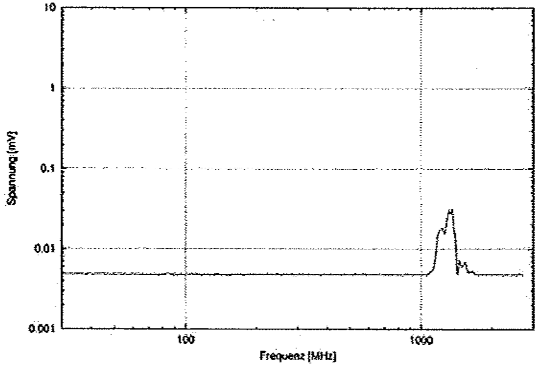

Figure 15 Microphone #7, with XCC connector, 10V/m, 30 % AM, RMS-values (amplified 10 dB)

7. ELECTROMAGNETIC EMISSIONS

For the sake of completeness, some notes on (electro-) magnetic emissions not into, but from the microphone. Although microphones are generally seen as "passive" devices they might generate disturbances in their closer surroundings. These could be of magnetic or electro-magnetic nature.

Some microphone types hold powerful magnets as part of their acoustic system. Especially in the case of ribbon microphones, these can produce interferences in neighbouring equipment, while moving coil microphones have a more "closed-loop" magnetic field. Only a small percentage of all microphones are of the ribbon type, and the typical user will rarely encounter such disturbances. In any case, [2, chapter 19] states methods for measuring the magnetic stray field.

As mentioned before, most microphone housings are constructed in metal, to provide a complete Faraday shield. Even though modern condenser microphones often include dc/dc-converters in their design, working in the low ultrasonic frequency range, this Faraday shield will effectively eliminate any potential emissions. Just as cable and connector in most cases are the path for electromagnetic interference entering the microphone, any residual ultrasonic signal components would be measurable directly on the cable with standard measurement equipment.

Last, on amplifiers with very wide input frequency range, comparatively large ultrasonic components might produce spurious level indication, especially with high amplifier gain settings. Whether such ultrasonic signals will produce audible disturbances, via demodulation in the amplifier circuit, depends on the amplifier's design, especially its capability of handling high frequent signals without distorting. Even though an "infinite" input frequency range might seem to be a desirable specification, amplifiers with band-limiting HF filters on the input are much less likely to be affected by residual ultrasonic signals.

8. ACKNOWLEDGEMENTS

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