Radio Frequency Susceptibility of Capacitor Microphones

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ABSTRACT

Neil Muncy has shown that improper termination of shield wiring, commonly called the pin 1 problem, couples noise currents flowing on a cable shield into audio circuitry through common impedance coupling. Inadequate bandwidth limiting of the microphone's line driver and decoupling of its phantom power circuits can also allow a path for radio frequency (RF) interference. This paper examines the susceptibility of modern microphones, describes a simple test to find problems, and offers simple solutions.

INTRODUCTION

Many modern capacitor microphones suffer from poor immunity to strong RF fields. One of the authors first experienced this problem in the 1970's, mostly with highly regarded large diaphragm microphones used near amplitude modulated VHF television transmitters. Because the interference could be significantly reduced by wrapping the microphone cable several times around a steel microphone stand very close to the point where it entered the microphone, thus improvising an RF choke, he concluded that the means of coupling was via the microphone cable.

Several facts suggested that improper circuit grounding might be a large part of the problem. First, Muncy's classic 1994 paper [1] highlighted improper grounding techniques that caused common impedance coupling, which he called "the pin 1 problem." Second, the manufacturers of some of those problematic microphones recommend the use of microphone cables that connect the shield to the shell of the connector. Recently, some have even urged the use of a new XL-connector that connects the cable shield to the shell rather than to pin 1, the designated shield contact. Both wiring methods clearly function as a "work-around" for microphones with a pin 1 problem! Third, many professional users of the problematic microphones report that it is necessary to connect the shield to the connector shell to avoid interference from nearby VHF and UHF television transmitters. Indeed, a visual examination of some of the most problematic microphones revealed improper termination of pin 1 in a manner that was likely to cause common impedance coupling of VHF and UHF currents into the microphone.

AES14 standardizes the wiring of XL connectors and includes a requirement that pin 1 shall be the designated shield contact. Connection of the shield to the shell is not part of the standard.

There is at least one very important reason why the shield of XL cables should not be connected to the shell of XL connectors. Star-connected grounding topologies are widely used in many parts of the world, including North America, and depend on there being a single connection to ground for the audio system at power frequencies. Wiring for audio tie lines in theaters, churches, and other facilities are usually mounted to conductive panels that are required by building codes to be grounded to conduit. When an XL cable having a connection between the shell and the shield is plugged into such a panel, it is common for currents to be set up on cable shields as a result of the connection, and for noise to be coupled into the audio system. A discussion of the sources of these currents and their impact on audio systems is beyond the scope of this paper, but there is ample coverage of the topic in the literature. [1, 2, 3, 4]

While a case can readily be made for improving the shielding of microphones and their wiring, there is no need for heroic efforts to do so. The proper shielding of microphones, proper termination of their wiring with attention to VHF and UHF impedances, and reasonably filtering their output wiring should be sufficient, and an analysis of the data provided by this paper supports that hypothesis.

MICROPHONE TESTS

A simple experiment was designed to evaluate each microphone's immunity to VHF and UHF fields and to identify the mechanism or mechanisms by which an interfering signal was being coupled to that microphone. It was hoped that the experiment would also allow an analysis of the relative importance of those mechanisms.

Microphones were connected, one at a time, to a microphone preamp using samples of several representative microphone cable types, and the output of the preamp monitored over a loudspeaker. Handheld VHF and UHF transceivers capable of transmitting at power levels ranging between 0.5 watts and 5 watts were used to produce an interfering field around 150 MHz and 450 MHz, and a digital cell-phone using pulsed modulation produced a field near 820 MHz. For the test, the transmitter with its attached antenna was moved around the microphone and the attached cable.

The microphone preamp was part of a Mackie 1604VLZ Pro mixer. An 8 m long section of Belden 1800F microphone cable ran from the preamp input to a 5 m long section of the test cables using the test connectors. Prior to beginning tests on the capacitor mics, the test setup was qualified by verifying that no interference was present with a dynamic microphone substituted for the capacitor microphone with the preamplifier operating at its highest gain.

Cable Types

Sets of XL male to XL female cables 5 m long were prepared for use in the tests. Five cable types were prepared, but only three were actually used with more than a few mics. Early results showed that the type of cable used had insufficient influence on the results to justify testing all of the mics with more than one or two cables. The cable types used were:

1. Belden 8412 A twisted pair cable with a braid shield.
2. Gotham GAC3 Three twisted conductors with two counterwound spiral shields. The third twisted conductor was wired in parallel with the shield.
3. Belden 1800F A 110 ohm, low-capacitance twisted pair cable with two counterwound spiral shields and a drain wire. The drain wire and the shield are in contact throughout and were wired together at each end.

Connectors and Their Wiring

The cables were wired four ways. In all cases, the shield was wired directly to pin 1 at each end.

1. The cables were wired per AES 14, with the shield connected only to the designated shield contact, pin 1.
2. The shields were connected both to pin 1 and to the connector shell (pin 0) using conventional XL connectors.
3. The shields were connected both to pin 1 and to the connector shell using Neutrik's so-called "Digital XLR" that allows a concentric D.C. termination of the shield to the connector shell. The shell of the female version of this connector also has a ribbed section intended to improve the connection between the shells of mating connectors.
4. The cables were terminated using newly developed connectors that make both a d.c. connection of the shield to pin 1, and an RF connection to the connector shell by means of an integral capacitor having concentric geometry, a concentric connection to the cable shield, and a concentric connection to the connector shell. These connectors also had a ferrite bead around pin 1, and the female connector had the ribbed construction of the Digital connector. The prototype connectors were used at both ends of a 5 m long cable.

The Microphones

A total of 45 microphones (including multiple samples of some types) from nine different manufacturers was tested. Microphones were chosen both on the basis of interest and their availability in time for them to be tested. To aid in analysis of the data, each was given a symbolic designation using letters and numbers to identify some of its key characteristics. The components of the designators, and their meanings, are:

First letter:
V - Vacuum tube electronics, transformer output
T - Solid state electronics, transformer output
D - Solid state electronics, no output transformer
Second Letter:
L - Large diaphragm (>1.5 cm)
S - Small diaphragm (0.75 cm - 1.5 cm)
M - Miniature diaphragm (<0.75 cm)
Third Letter (optional)
C - Custom cable
A - Attached cable (lavalier, choir hanger, etc.)
O - Omni pattern (only)
First digit indicates manufacturer (not alphabetically related)
Second digit, if present, indicates a second micro-

phone from the same manufacturer of the same generic type.
10, 15, 20 - Indicates the maximum switched attenuation in dB, if any, between the capsule and the first electronic stage.

The tested microphones included:

- Manufacturer #1
    - DS1 - A current production model with interchangeable capsules.
    - DL1-1 - A current production unit.
    - DL1-2-10 - A current production switchable pattern unit.
    - TL1-1-10 - About 30 years old, no longer in production.
    - TL1-2-10 - About 30 years old, still in production, switchable pattern.
    - VL1 - A current production unit.
- Manufacturer #2
    - VL2-20 - A current production unit.
    - TL2-20 - A current production switchable pattern unit.
    - DS2-10 - A current production model with interchangeable capsules.
    - TS2-1-20 - About 30 years old, uses interchangeable capsules, no longer in production.
    - TS2-2-15 - A current production unit.
    - TM2 - A current production podium microphone with interchangeable capsules.
    - TMA2-1 - A current production miniature, interchangeable capsule with an auditorium hanger.
    - TMA2-2 - A current production boundary mic.
    - TMA2-3 - A current production boundary mic.
- Manufacturer #3
    - TS3-10 - About 20 years old, still in production, uses interchangeable capsules.
    - DL3-1-15. - A current production unit.
    - DL3-2-15 - A current production unit.
    - TSA3 - A current production coincident microphone pair for M/S use.
    - TMA3-1 - A current production sub-miniature lavalier microphone.
- Manufacturer #4
    - DL4-1-10 - A current production unit.
    - DL4-2-10 - A current production unit.
    - VL4 - A current production unit.
    - DS4 - A current production unit.
    - TS4-1-10 - For handheld vocal use.
    - TS4-2-10 - For handheld vocal use.
    - TMA4-1 - A current production podium mic.
    - TMA4-2 - A current production podium mic, similar to TMA4-1 but with a longer gooseneck extension section.
- Manufacturer #5
    - TMO5 - About 20 years old, still in production.
- Manufacturer #6
    - DL6-1-10 - Switchable pattern. Current production.
    - DL6-2 - A current production handheld vocal microphone.
- Manufacturer #7
    - TMO7 - A low cost measurement microphone.
    - TM7 - A low cost stereo array.
- Manufacturer #8
    - TMO8 - A current production unit.
    - TM8 - A current production handheld vocal microphone.
- Manufacturer #9
    - DS9 - About 30 years old, still in production, uses interchangeable capsules.

Test Generators

Two types of generator were used. They were:

A digital cell-phone manufactured by Motorola for the Nextel system. The unit transmits very short duty cycle digital pulses with repetition rates in the low audio spectrum using Time Division Modulation around 820 MHz with peak power on the order of 2 watts. The modulation characteristic can be viewed as a 100% amplitude modulated signal with a square wave source. The signal will be demodulated by any mechanism that responds to amplitude modulation, including a square law detector, slew rate limiting, and fundamental overload (clipping). Detected audio will have fundamental energy in the low audio spectrum and be very rich in harmonic content. The transmitter output power is varied in response to variations in received signal strength, but this variability was not found to be a factor in the testing.

Low power handheld FM transceivers operating on frequencies around 150 MHz and 450 MHz. To produce a detectable signal, these units must be turned on and off rapidly to simulate amplitude modulation. Most units of this type have somewhat soft turn-on characteristics, so the detected audio tends to be less audible.

Laboratory Test Procedures

The microphone under test was mounted on a boom stand approximately 2 m above the floor, with the boom extended approximately horizontally so that the test cable dropped to the wood floor of the laboratory approximately 0.5 m from the stand. An 8 m length of Belden 1800F, wired per AES14, ran through an open doorway to connect the test cable to a small preamplifier/mixer in an adjacent room. The output of the mixer fed a compact, full range loudspeaker in the same room with the mixer.

The microphone under test was pointed away from the open door and set to its minimum sensitivity using any switchable attenuator integral to it. All switchable and variable equalization on both the microphone under test and the preamplifier were set for flat response (although no attempt was made to compensate for any equalization built into microphones). The preamplifier and mixer gains were then adjusted so that they were just below the threshold of acoustic feedback.

The test generators were then caused to transmit (one at a time). For the cell-phone, a call was initiated. For the transceiver, the push-to-talk switch was very quickly continuously operated and released to simulate 100% amplitude modulation. Both generators were moved all around the microphone under test and along the microphone cable for whatever distance was required for any observed interference to become inaudible. Notes were taken on the relative susceptibility of each microphone to each interference source using a subjective scale based on the loudness of the interference and the proximity required of the generator to cause the interference. The scale ranged from severe to very strong, strong, moderate, mild, very mild, slight, very slight, and inaudible. The tests were then repeated for the connector wiring configurations. All testing was done by the same person and in the shortest practical time frame to minimize variations in the subjective rating system. Tests were repeated at least once for most microphone types.

Interference was considered severe if the generator at a distance of 30 cm from the microphone or its cable caused interference at a level roughly equivalent to a person speaking into the microphone at a distance of 15 cm. Interference was considered mild if hot spots of not very loud interference could be found as the generator's antenna was moved along the cable in close physical contact with it. The authors estimate each subjective step to represent a difference in susceptibility to the interfering field on the order of 3-6 dB. However, since all detection results from nonlinear processes, such a judgment is difficult to make with any degree of certainty, and the estimate should be considered only an educated guess.

Field Test Procedures

Microphones were set up one at a time in the window of two buildings that had exposure to moderately strong VHF transmitters. The various test cables connected the microphone to the preamplifier/mixer, and the microphone was monitored on headphones. Both locations had line of sight to some of the transmitters but one was shadowed to some of the highest power transmitters. A Hewlett Packard 8590D spectrum analyzer connected to the shield of one of the 5 m long microphone cables measured the signal into a 50 ohm load.

The RSS (square root of the sum of the squares) value of the received broadcast signals at location #1 was on the order of 275 mV and 5.5 ma into the 50 ohm analyzer. The predominant signals were FM broadcast transmitters in the 88-108 MHz band and two television broadcast transmitters in the low VHF TV band (54-88 MHz). High band VHF (174-216 MHz) television and UHF television (470-800 MHz) transmitters were mostly shadowed by more than 20 dB. Location #1 was approximately 1.6 km from the predominant transmitters. At location #2, a recording studio approximately 4.5 km from both transmitter sites, field strength was approximately 6 dB lower. At this location, low band VHF television signals were most significant, with channel 2 (54-60 MHz) being predominant.

A third series of tests took place in an automobile that was parked at six locations within 2 km of the two buildings – the John Hancock Center and Sears Tower -- on which virtually all of Chicago television and FM broadcast transmitters are located. At one location roughly 1 km from one of the buildings and 1.5 km from the other, microphones were set up on a stand on the sidewalk, but acoustic noise limited the sensitivity of that arrangement, so the balance of the testing was done inside the automobile. Some of the locations were as close as 0.5 km, three were 1 km from one of the buildings but 3 km from the other, and some microphones were tested while driving around the block underneath the Hancock building. For the tests, the microphones were connected one at a time to a battery-powered Sound Devices preamplifier and monitored on headphones. Microphones were tested with the standard connector, the capacitive connector, and the digital connector.

At all locations, the microphone and cable under test were given the greatest practical exposure to the RF field by placing them in the large front window, and both microphone and cable were manipulated to find hot spots of interference. This simulated the real world effect of setting up microphones at varying locations and orientations to pick up a performance.

TEST RESULTS

Laboratory Testing

DS1 - There was no susceptibility at 150 MHz or 450 MHz, and very mild cell-phone interference was eliminated by the capacitive and digital connectors. Connecting the shield to both pin 1 and pin 0 of conventional connectors had no effect as compared to a connection to pin 1 only.

DL1-1 - There was moderate 150 MHz, 450 MHz, and cell-phone interference with the standard connector. Capacitive and digital connectors reduced 150 MHz interference to slight and eliminated 450 MHz and cell-phone interference. Connecting the shield to both pin 1 and pin 0 of a conventional connector reduced 150 MHz interference and cell-phone interference to mild, and eliminated 450 MHz interference.

DL1-2-10 - Severe cell-phone interference, strong 450 MHz interference, and very mild 150 MHz interference with the standard connector were eliminated by both capacitive and digital connectors. Connecting the shield to both pin 1 and pin 0 of a conventional connector reduced cell-phone interference to strong, 450 MHz to moderate, and eliminated 150 MHz interference.

TL1-1-10 - Severe interference at 150 MHz, 450 MHz, and from the cell-phone with the standard connector were all completely eliminated by both the capacitive and digital connectors. Connection to pin 1 and pin 0 with a standard connector reduced 150 MHz interference to very mild and 450 MHz interference to mild, but had no effect on cell-phone interference as compared to a connection to pin 1 only.

TL1-2-10 - Severe cell-phone and moderate 150 MHz interference with the standard connector were reduced to mild cell-phone interference and no 150 MHz interference with the capacitive and digital connectors; and reduced to mild by connection of the shield to both pin 1 and pin 0 of a conventional connector.

TL2-20 - Severe cell-phone interference was unaffected by connector or cable type. Moderate 150 MHz interference was completely eliminated by capacitive and digital connectors and by connection of the shield to both pin 1 and pin 0 of a conventional connector.

DS2-10 - Strong 150 MHz interference with the standard connector was reduced to slight with both capacitive and digital connectors. Strong cell-phone interference was eliminated by capacitive and digital connectors. Connection of the shield to both pin 1 and 0 of a conventional connector had little if any effect on immunity as compared to a connection to pin 1 only.

TS2-1-20 - Moderate cell-phone and mild 150 MHz interference was eliminated by capacitive and digital connectors. Connection of the shield to both pin 1 and pin 0 of a conventional connector had no effect on immunity as compared to a connection to pin 1 only.

TS2-2-15 - Moderate 150 MHz interference with a standard connector was almost completely eliminated with capacitive and digital connectors. Strong cell-phone interference with a standard connector was reduced to slight by a capacitive connector and mild by a digital connector. Connection of the shield to both pin 1 and pin 0 of a conventional connector had no effect on immunity as compared to a connection to pin 1 only.

TM2 - Very mild 150 MHz and cell-phone interference with a standard connector was eliminated by both capacitive and digital connectors, and by connection of the shield to both pin 1 and pin 0 of a conventional connector.

TS3-10 - Strong cell-phone interference, very mild 150 MHz interference, and mild 450 MHz interference with the standard cable were reduced to very slight cell-phone interference and no 150 MHz interference by both capacitive and digital connectors. Connection of pin 1 to pin 0 of a standard connector reduced 150 MHz interference to very slight and 450 MHz interference to very mild, but had no effect on cell-phone interference as compared to a connection to pin 1 only.

DL3-1-15 - Strong cell-phone and 150 MHz interference with the standard connector were reduced to very slight by capacitive connector and eliminated by digital connector. Connection of pin 1 to pin 0 of a conventional connector eliminated 150 MHz interference and reduced cell-phone interference slightly as compared to a connection to pin 1 only.

DL3-2-15 - Mild cell-phone and 150 MHz interference with the standard connector were reduced to very slight cell-phone interference and very mild 150 MHz interference by both capacitive and digital connectors. Connection of the shield to both pin 1 and pin 0 of a conventional connector increased 150 MHz interference to mild but reduced cell-phone interference to moderate.

DL4-1-10 - There was mild 450 MHz and cell-phone interference with standard connector. Cell-phone interference was reduced slightly by both capacitive and digital connectors, but 450 MHz was unaffected. Cell-phone was reduced only slightly and 450 MHz was unaffected by connection of the shield to pin 1 and pin 0 of a standard connector as compared to a connection to pin 1 only.

DL4-2-10 - Same as DL4-1-10.

DS4 - Strong cell-phone interference with the standard connector was eliminated by both capacitive and digital connectors. Connection of the shield to both pin 1 and pin 0 had no effect on interference as compared to a connection to pin 1 only.

TS4-1-10 - Very strong cell-phone interference with the standard connector was eliminated by both capacitive and digital connectors. Connection of the shield to both pin 1 and pin 0 of a standard connector reduced cell-phone interference to strong.

TS4-2-10 - There was severe 450 MHz and cell-phone interference, including symptoms of output stage oscillation or the power supply collapsing (motorboating) with the standard connector. 450 MHz interference was eliminated and cell-phone interference was reduced to mild with both capacitive and digital connectors. Connection of the shield to both pin 1 and pin 0 reduced 450 MHz and cell-phone interference to very strong, but instability remained.

TMA4-1 - Strong cell-phone interference with the standard connector was reduced only slightly by the capacitive connector but was reduced to very mild with the digital connector. Connection of the shield to both pin 1 and pin 0 of a standard connector had no effect as compared to a connection to pin 1 only.

TMA4-2 - Strong cell-phone interference with the standard connector was eliminated by both capacitive and digital connectors. Connection of the shield to both pin 1 and pin 0 of a standard connector had no effect as compared to a connection to pin 1 only.

TMO5 - Strong cell-phone interference with the standard connector was reduced to slight with the capacitive connector and was eliminated by the digital connector. Connection of the shield to both pin 1 and pin 0 reduced cell-phone interference to mild.

DL6-1-10 - There was severe cell-phone interference, but no 150 MHz or 450 MHz interference, with the standard connector. Cell-phone interference was reduced to slight with both capacitive and digital connectors. Connection of the shield to both pin 1 and pin 0 of a standard connector increased 150 MHz interference to very mild and reduced 450 MHz interference to mild, but reduced cell-phone interference to very strong.

DL6-2 - There was moderate cell-phone, mild 150 MHz, and moderate 450 MHz interference with the standard connector. 450 MHz interference was reduced to slight and cell-phone interference to mild with both capacitive and digital connectors. Connection of the shield to both pin 1 and pin 0 of a standard connector had no effect on cell-phone interference as compared to a connection to pin 1 only, but reduced 150 MHz interference to very mild and 450 MHz interference to mild.

TMO7 - Strong cell-phone interference with the standard connector was completely eliminated by both capacitive and digital connectors. A connection of the shield to both pin 1 and pin 0 of a standard connector reduced cell-phone interference to slight.

TM7 - With the standard connector, moderate 150 MHz interference was coupled directly into the microphone, most likely the result of inadequate shielding. Strong cell-phone interference with the standard connector was reduced to moderate with both capacitive and digital connectors, and much of the remaining interference seemed to be related to the inadequate shielding. Connection of the shield to both pin 1 and the shell of a standard connector had little effect as compared to a connection to pin 1 only.

TMO8 - Strong cell-phone interference with the standard connector was eliminated by the capacitive connector, while the digital connector reduced it only slightly. Very mild 150 MHz interference was eliminated by both capacitive connector and digital connectors. Connection of the shield to both pin 1 and pin 0 slightly reduced 150 MHz and cell-phone interference as compared to a connection to pin 1 only.

TM8 - Mild cell-phone interference with a standard connector was eliminated by both capacitive and digital connectors. Interference was not reduced by connecting the shield to both pin 1 and pin 0 of a standard connector as compared to a connection to pin 1 only.

DS9 - Strong cell-phone interference was reduced to slight and very mild 150 MHz interference was eliminated by both capacitive and digital connectors.

Microphones with proprietary cable assemblies

This group includes one coincident stereo microphone pair, microphones using power supplies for vacuum tube electronics, and microphones using powering adapters for lavalier and auditorium-hanging capsules.

VL1- There was moderate interference at 150 and 450 MHz, strong interference with cell-phone.

VL2-20 – There was very mild 150 MHz interference and strong cell-phone interference.

VL4 - There was moderate cell-phone interference.

Changing the XL3 connector at the power supplies of the vacuum tube microphones had no effect on their susceptibility.

TMA2-1 - There was strong cell-phone interference along the auditorium hanging cable, continuing along the standard XL cable. The capacitive and digital connectors eliminated susceptibility to interference along the XLR cable.

TMA2-2 - There was mild 150 MHz and 450 MHz susceptibility as well as severe cell-phone susceptibility along the cable between the capsule and the power supply/line driver, and continuing along the XL cable. Capacitive and digital connectors did not help.

TMA2-3 - Cell phone interference was only slightly better than with the TMA2-2, but with no interference from 150 or 450 MHz.

TMA3-1 - There was severe cell-phone susceptibility along the cable between the capsule and power adapter and continuing along the XL cable. Susceptibility along the XL cable was only slightly reduced by the capacitive or digital connector.

TSA3 - There was strong cell-phone and mild 150 MHz interference. Both were unaffected by connector or cable type.

Field Test Results

Location #1 was acoustically quite noisy, so it took a significant EMC disturbance to be audible. When the standard connector wired per AES14 was used, severe interference was observed with microphone TL-1-10. An assistant described it as being "nearly as loud as my voice" as I stood next to the microphone. Interference was audible but not prominent (as compared to the acoustic noise level) in DL1-1, DL1-2-10, and TS2-2-15. In all cases, interference became inaudible when cables using the capacitive connector or the digital connector were substituted for those using the standard connector. No interference was observed with any of the other microphones. This is not surprising given the very high acoustic noise level.

Location #2 was the control room of a recording studio (selected because it had a window providing line of sight to both transmitter sites), so it was acoustically very quiet. Microphones TL1-1-10, DL1-1, and DL1-2-10 demodulated the television broadcast signal as a loud buzz, with TL1-1-10 and DL1-1 having the greatest susceptibility. No other microphones that were tested in the lab exhibited susceptibility to the fields present at location #2. The studio owned samples of microphone TL1-1-10, TL1-2-10, and another microphone type from manufacturer #9, designated DS9-2-10. Those three microphones were also tested at location #2. Results for TL1-1-10 and TL1-2-10 were the same as for samples tested in the lab. DS9-2-10 demodulated the television broadcast signal at about the same level as TL1-1-10. DS9 was not tested at location #1. All broadcast interference was eliminated by use of the capacitive and digital connectors.

Microphone DS9-2-10 was tested with the cell phone and received severe interference, The cell phone interference was reduced to moderate by both the capacitive and digital connectors.

Tests In The Automobile

Measurements were made mid-day during the working week. The test environment inside the automobile was much less noisy (acoustically) than location #1 but much noisier than location #2. This allowed moderately low levels of interference to be observed. A battery-powered spectrum analyzer was not available, but a 200 MHz Fluke Scopemeter indicated -11 dBV at one location within about 1 km of Sears Tower using a 20 cm test lead as an antenna. Not all of the microphones were tested in the automobile.

It should be noted that the transmitting antennas are approximately 450 m above the ground and have significant directivity in the vertical plane, but are essentially omnidirectional in the horizontal plane. Thus, taking vertical directivity of the antenna into account, a location at street level very close to the building does not necessarily have greater field strength than one at 1 km, and the drop in field strength from 1 km to 4 km may be closer to 9 dB than 12 dB. Indeed, interference noted at test locations 1 km from a transmitter site at street level was not much greater than that noted at location #2 which was 4.5 km from the two buildings.

Microphones DL1, DL1-2-10, and TL1-1-10 received significant interference at every location, but at each location the interference was eliminated by the capacitive and digital connectors.

Microphones DL6-1-10 and DL6-2 received interference at two locations, both within 1 km of one or the other of the two transmitter sites. Interference in both mics was eliminated by the capacitive and digital connectors.

Microphone TS2-2-15 received interference at one location within 1 km of Sears Tower that was eliminated by both capacitive and digital connectors.

Microphone TS4-2-10 received significant interference at two locations with the standard connector that was eliminated by both capacitive and digital connectors.

Only one microphone, DL4-1-10, received interference with the capacitive or digital connectors, and it received interference at only two locations, both of which were within 1 km of one or the other of the two transmitter sites.

Microphones DS1, TL2-20, DS2-10, TS3-10, TL3-1-10, and TL3-2-10 were free of interference at all locations.

ANALYSIS OF THE DATA

The Pin 1 Problem

The data clearly support the hypothesis that improper or inadequate connection of pin 1 of the cable connector is the primary cause of poor immunity. With all but two self-contained microphones (that is, those without proprietary cables connecting them to a power supply, power adapter, or line driver), substitution of the capacitive or digital connector on the mating cable either significantly improved immunity, or in most cases completely eliminated any interference. With many of the microphones, connecting the shield both to pin 1 and pin 0 of the microphone cable also improved immunity.

Shield-Current-Induced Noise And Bandwidth Limiting

Logic suggests that if shielding is properly terminated by the digital connector to the extent that common impedance coupling is reduced to a very low level, any remaining susceptibility might be the result of voltage being induced on the signal pairs. Brown and Whitlock have shown [4] that current flowing on the shield of a twisted pair audio cable at radio frequencies will cause a differential mode signal to be induced on the signal pair that is proportional to the frequency of the excitation to at least 4 MHz, and have hypothesized that this mechanism will continue to increase through the high frequency spectrum and be significant into at least low VHF. Once pin 1 problems had been reduced by the capacitive and digital connectors, the remaining susceptibility could be observed as the generator was moved along the XL cable for 1-2 m. This suggests that the means of coupling is via current and voltage induced onto and carried by the signal pairs, rather than due to any break in the shielding around the microphone. Thus, data suggest that inadequate bandwidth limiting (that is, RF filtering) of the signal conductors is the mechanism for coupling interference into microphones that still have susceptibility when the capacitive and digital connectors are used.

Microphones TL2-20, DL4-1-10, and DL4-2-10 are examples of those needing bandwidth limiting. Such simple measures as ferrite beads, common mode chokes, and small value bypass capacitors (on the order of 100 pf) on the signal pair can provide the needed filtering.

Of the three vacuum tube microphones tested, two had very poor immunity to the cell phone and one was only fair. All three had at least moderate susceptibility at 150 MHz.

There was little correlation between retail price and quality of EMC performance. Some of the most expensive products had the poorest EMC performance when used with cables properly wired per AES14.

Microphones with Vacuum Tube Electronics

Because vacuum tube microphones are attached to power supplies by long proprietary cable assemblies, changing XL3 connectors at their power supplies had no effect on their susceptibility at VHF and UHF. This issue can be addressed only within the microphone or the connector mating with the microphone's internal connector. None of these microphones were tested in the field. Laboratory results suggested that VL1 might receive interference from very strong broadcast television fields, but that the other microphones tested would not.

Capsules on Extension Cables

All of the tested microphones that had miniature cables connecting a miniature capsule to a power/line driver adapter exhibited very poor immunity to cell-phones, and two had mild susceptibility to 150 MHz and 450 MHz. The medium impedance and usually unbalanced nature of this connection is suspected as a cause. Likewise, the medium impedance connection of a lavalier microphone to a wireless transmitter is suspect as a contributor to anecdotal reports of interference when a person wearing the microphone is very close to RF noise sources. This mechanism is also worthy of attention.

Test Generators and the Real World

Handheld VHF and UHF transceivers and cell-phones are widely used in venues where sound reinforcement systems are used, so their use as a test generator is directly relevant. Comparison of the laboratory data with field data shows reasonable correlation between 150 MHz susceptibility and susceptibility to VHF broadcast signals. The microphones with the greatest susceptibility to 150 MHz and 450 MHz also had the greatest susceptibility to broadcast signals.

It is important to understand the difference between the fields produced by handheld transceivers and those produced by high power broadcast transmitters in the same frequency spectrum. By virtue of inverse square law and the nature of their antennas, handheld transceivers, including cell-phones, produce very high field strengths only at very close range. They are able to induce fields on the order of 100 volts/meter at distances of a few cm, so they can induce relatively high voltages and currents in a short length of audio cable. Broadcast transmitters are far more powerful, but they are also far more distant -- even at distances as short as a few km, they produce much lower field strengths, but they can do so over a much greater length of cable.

Thus, while a handheld transceiver may cause strong interference within 30 cm or so of a microphone or for 1 or 2 m along a cable, it is unlikely to cause interference at a greater distance. On the other hand, the broadcast transmitter can induce voltage and current in audio wiring over a wide area to the extent that the wiring is not shielded.

A major advantage of using a handheld transceiver as a test generator is that it can be used as an injection-style probe to understand the mechanism by which interference is entering a system. The major disadvantage is that like any RF generator, it must be used with great care to avoid running afoul of national regulations governing radio transmitters. It was this probe-like behavior that made it clear that microphone TM7 was poorly shielded.

Using the cell-phone as a probe exposed a similar shielding failure at 800 MHz around a 15 mm slot opening in the shell of microphone TS2-2-15 that allows user access to an attenuator switch. Cell-phones didn't exist 20 years ago when this very nice vocal microphone was introduced.

MECHANISMS OF RF INTERFERENCE

Detection

At first glance, it may not be obvious how a stray RF signal could cause problems in a microphone or other audio circuit. The RF is not heard or recorded directly, being far above the audio spectrum. Even if the RF signal is mixed directly with the audio there might be no interference, as the output spectrum is simply the sum of the audio components and the RF components, each occupying its own frequency spectrum. Indeed, below a certain threshold amplitude for each of the circuits examined, no audio frequency interference is noted.

When any two signals are mixed and pass through a non-linear device such as a semiconductor junction or a vacuum tube, each signal modulates the other, and sum and difference products are generated for all of the discrete frequencies present in the mixed signals.

Transmissions from an AM broadcast transmitter consist of a radio carrier frequency and a pair of sidebands for every frequency contained in the modulating signal. For example, an AM station transmitting an audio sine wave of 1 kHz on its assigned frequency of 1 MHz will transmit signals at 999 kHz, 1,000 kHz, and 1,001 kHz. That 1 kHz signal will be detected when it passes through a circuit that responds non-linearly to it, because the non-linearity will produce sum and difference components of the signals it sees, as well as sum and difference signals of whole number multiples (harmonics) of the signals. In this example, the first order differences are two signals at 1 kHz and signals around 2 MHz. Higher order differences (harmonics) will be present at higher radio frequencies and also within the audio passband. The 1 kHz signal is audio, and will be heard as an interfering signal if it appears in a audio circuit.

Detection is not a linear phenomenon. The RF signal amplitude must reach a threshold within some circuit element such that the element exhibits non-linear behavior to the signal. The threshold is a function of circuit parameters. The most easily detected signals are those that are amplitude modulated. The video component of television signals and AM radio broadcasting in the 500kHz to 1.8 MHz band are common forms of amplitude modulation.

The primary mechanisms for amplitude modulation are (1) square law detection, which can occur in virtually any semiconductor junction; (2) detection due to slew rate limiting; and (3) fundamental overload (clipping, rectification). The audio circuitry in virtually any capacitor microphone will function as a detector if sufficient RF energy reaches it. An interfering signal may be too low in level to be detected in the first electronic stage through which it passes, but might be detected by a subsequent stage after being amplified by the first stage. This is a critical reason for limiting the bandwidth of audio circuits to the absolute minimum needed for accurate magnitude and phase response.

Frequency modulated radio signals (FM) can also be detected by audio circuits, and four of the microphones tested did so at test location #1. Frequency modulated signals also consist of a carrier and sidebands, but the relationship is more complex than the simple sum and difference. FM signals are most commonly detected when they are converted to AM by some frequency response variation in either the transmission path or This mechanism is called slope detection.. Again, non-linearity of an audio circuit that also contains the radio signal is required for detection to take place.

Even un-modulated RF signals can cause interference. One mechanism is rectification due to non-linearity detection of the RF signal upsetting the bias of an active stage. RF susceptibility is often either caused by or accompanied by circuit instability (oscillation), and oscillating circuits can detect FM signals.

The first line of defense in the design of audio circuits is to use a circuit design that will tolerate a fairly high level of RF before non-linear mixing or detection begins.

Circuit Balance at RF

The second approach is to design circuits so that they inherently rejects RF energy by virtue of their circuit balance. Many microphones are designed with balanced topology in some or all of their active circuits. A balanced circuit provides significant rejection of common-mode signals. On the surface this sounds promising, except that while such circuits may achieve balance at audio frequencies, they seldom maintain that balance above a few hundred kHz and may even have common mode gain at higher frequencies.

Attenuation of RF

Any good design should concentrate on minimizing the level of RF getting into the microphone (what Muncy calls "keeping the fox out of the henhouse"). It is important to proceed carefully here as the circuit can be made unnecessarily complex if the effect of each component is not clearly understood. The various methods used by the microphone and connector manufacturers described here are a combination of series and shunt reactances that simply produce an attenuator between RF signals and the active circuitry of the microphone so that the signal cannot reach the amplitude required to cause detection.

Shunt capacitors can effectively short the RF voltage on signal conductors to circuit common or to the housing of the microphone. The reactance of these paths should be no more than a few ohms, and must remain low through extremely high frequencies. The construction of this capacitor is critical if the impedance is to remain low -- virtually all real components will have enough inductance that at some very high frequency the inductive reactance becomes greater than the capacitive reactance. Above that frequency, the capacitor is no longer able to short out the signal.

Series inductors can effectively produce a high impedance path for RF signals. A simple network composed of a series inductor and shunt capacitor can block the "through" path and provide a short circuit for the interfering signal. Real components are rarely that simple at television and cell phone frequencies. For example, the stray capacitance between the turns of an inductor may short out its inductance and cause it to look like a low capacitive reactance rather than an inductor.

Often a combination of components must be used to overcome these physical shortcomings. For example, wire-wound inductors that have sufficient inductance to block signals from a few hundred kHz up to a few tens of MHz (when their stray capacitance renders them useless) can be used in series with ferrite beads that have negligible effect at lower frequencies but provide high series reactance up to several hundred MHz.

The non-linear nature of RF detection and susceptibility has important implications both to design and application. Total elimination of RF from audio circuitry can be quite costly. Luckily, this level of performance is not required. All that is required is to reduce the level below that which is audible, and audibility is exponentially related to the strength of the interfering signal.

Thus, a 3 dB reduction in the interfering signal, whether by filtering, shielding, orientation of a microphone cable, or some combination thereof, can result in a reduction of 6-12 dB in the audibility of the interference when more than 3 dB above the threshold of detection, and an even greater reduction when closer to the threshold.

This knowledge is quite useful. In the field, for example, mild RF interference can be made inaudible simply by wrapping the microphone cable a few turns around a metallic microphone stand and minimizing the exposed loop of cable between that point and the microphone. Such an expedient must be used with care, however, since it can also degrade mechanical isolation of a microphone in a vibration-isolating mount.

This principle is important in establishing design criteria as well. RF attenuation need only be sufficient to prevent detection under worst case field conditions. With respect to VHF and UHF broadcast interference, worst case would appear to be a studio located in a high rise building a few hundred meters from the transmitting antenna on the same side of the building as the exposure and with limited shielding from the building. Such conditions do exist in most major cities, but none were used as test locations for this experiment.

With respect to LF and MF susceptibility, worst case is probably a wood-frame church or studio within 2 km of a 50-500 kW AM broadcast transmitter, and with microphone wiring using foil/drain shielded cable that is not installed in grounded metallic conduit. Brown and Whitlock have shown that rather high levels of RF will be induced on the signal pair in such an environment due to shield-current induced noise. [4]

With respect to handheld transmitters, worst case is probably represented by a cell phone in the pocket of a performer or talker near a microphone. While VHF and UHF transceivers can cause interference if used within 1 m of the most susceptible microphones, the likelihood of such use is low, and providing sufficient immunity to reject VHF and UHF broadcast transmitters in the worst case environment noted above would almost certainly also reject the transceiver.

The use of UHF and even SHF frequencies is increasing rapidly. Most cell phones operate just below 1 GHz, but a newly allocated cell phone band around 2.2 GHz is increasingly active. Bands allocated to IEEE 802.11b communications (Wi-Fi) are in wide use at 2.4 GHz and coming into use at 5.8 GHz. While most transmitters on these frequencies radiate relatively low power, their possible proximity to microphones and use of pulsed modulation can make them potent interference sources. Thus, providing a reasonable level of immunity to at least 6 GHz should be a design objective.

EXAMINATION OF THE MICROPHONES

Some microphones that exhibited relatively poor immunity were disassembled and termination of the cable was studied. Without exception, the microphones having the poorest immunity had an obvious "pin 1 problem." Some examples are presented in Figures 1-6.

Fig 1 shows an obvious pin 1 problem in microphone DL1-1. Pin 1 is connected to the chassis with the black wire on the right, but pin 1 also is connected to the circuit board with the orange wire. The orange wire appears to be circuit ground for the printed circuit board, but the voltage on pin 1 is in series with it. Fig 7 shows why this is a bad idea. At test location #1, the shield carried about 5.5 mA of VHF broadcast signals.

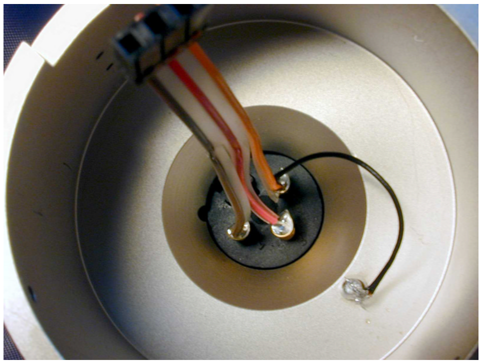

Fig 1 - Microphone DL1-1.

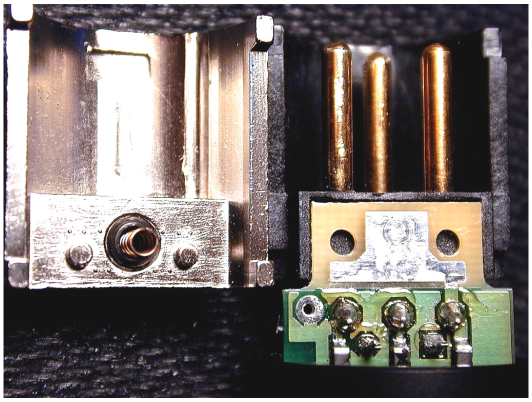

Fig 2 - The XL connector of microphone DS2-10.

Microphone DS2-10 also exhibits a pin 1 problem. The XL connector (Fig 2) is split into two halves, one of which is soldered to the circuit board. The other half is held in contact with the microphone tubular shell by its position within the shell. The tiny spring (visible at the lower center of the left half of the connector) makes contact with the conductive part of the circuit board on the right half of the connector, which is soldered to the circuit board. The spring appears to be a poor connection for the shield, both because of its inductance and the poor contact it makes at one end to the shell of the microphone and at the other end to the circuit board. Again, the printed circuit board goes to ground via this common impedance.

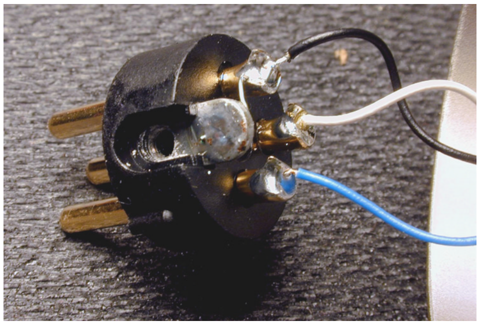

Fig 3 - Connector wiring in microphone DL1-2-10

Microphone DL1-2-10 has a pin 1 problem. The black lead goes to the circuit board, most likely to circuit common, making the tiny jumper and the connector shell screw a common impedance at VHF and UHF. One of author Brown's samples of this microphone was modified by removing the black lead from pin 1 and connecting it to the microphone shell at a distance from the connector. This simple modification reduced susceptibility by an estimated 3 dB.

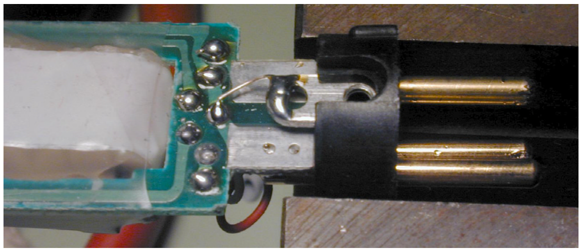

Fig 4 - Microphone TS2-2-15

Microphone TS2-2-15 has yet another kind of pin 1 problem. At first, the tiny wire between pin 1 and the contact for the shell was suspected. In fact, the pin 1 problem was caused by poor contact between the connector shell screw and the shielding enclosure of the microphone! Tightening that screw improved immunity by about 3 dB.

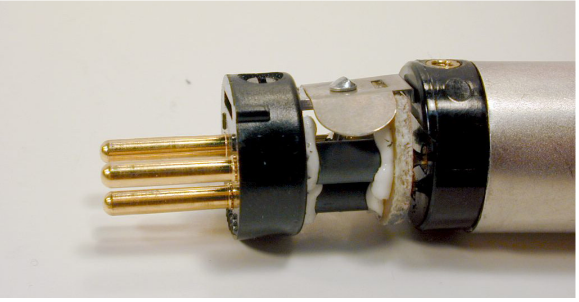

Fig 5 - Microphone DL3-2-15

Ferrite beads and 100 pF bypass capacitors on the signal leads provide effective filtering of microphone DL3-2-15 (Fig 5). The large copper strap at the top of the assembly bonds pin 1 to the shell of the microphone (on the side of the connector not visible in this photo).

In the microphone shown in Fig 6, pin 1 is bonded to the shell of the microphone with a very short, very wide copper strap. With both this microphone and that shown in Fig 5, there is still a bit of common impedance coupling via the resistance and inductance of the bonding strap. The rectangular block on the left is a common mode choke, but the ferrite beads are missing. This microphone has good immunity up to about 300 MHz, but immunity degrades at 450 MHz and with a cell-phone. This microphone was tested in the manufacturer's lab but was not available for testing with the experimental connectors.

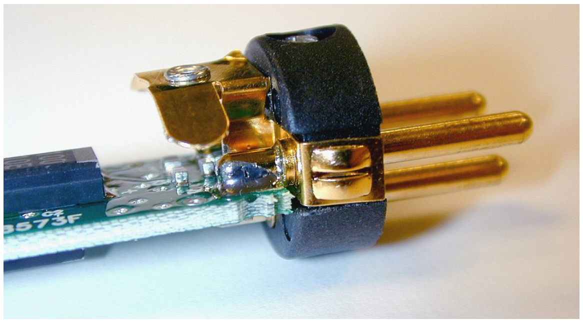

Fig 6 Another microphone from manufacturer #3.

The Pin 1 Problem in Microphones

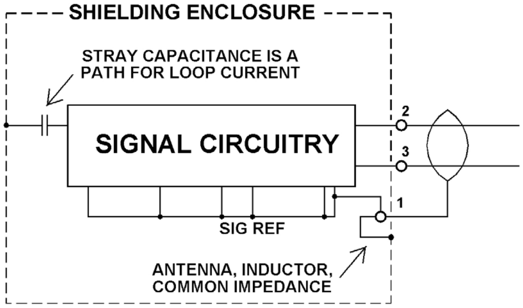

Fig 7 - A typical pin 1 microphone problem [5]

Figure 7 illustrates how shield termination in capacitor microphones sets up common impedance coupling (the pin 1 problem). The connection shown as a loop between pin 1 and the shielding enclosure can be a screw, (Fig 3, 4), a loop of wire (Fig 1, 3, 6), or even the spring and questionable contacts shown in Fig 2.

The scheme shown in Figure 8 avoids a pin 1 problem. The cable shield is connected to the chassis by the shortest possible path (in the university it was called a "zero length" lead to emphasize the importance of minimizing its inductance). If the shield connection is made to the outside of the shielding enclosure, skin effect will further reduce noise coupling into the microphone enclosure by causing shield current to flow on the outer surface of the enclosure.

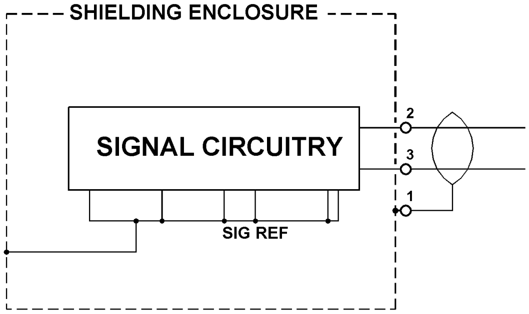

Fig 8 - A scheme that avoids a pin 1 problem.

CONCLUSIONS

1. Some form of pin 1 problem is the primary cause of poor immunity to VHF and UHF interference in capacitor microphones, and degrades the immunity of almost every microphone tested.
2. Inadequate filtering of the signal conductors is a contributor to susceptibility in some microphones, and in many microphones becomes the limiting factor once the pin 1 problem is eliminated.
3. Use of the prototype cable-mounted connector having a concentric capacitive termination of the shield to the shell significantly improves the immunity of most microphones to VHF and UHF fields. In all cases, the concentric capacitor was greatly superior to a d.c. connection of the shield to both pin 1 and the shield of a conventional connector. In almost all cases, the concentric capacitor was equal in effectiveness to the concentric d.c. connection of the shield to the shell, and in the few cases where it was not equal, its performance was within a few dB of the d.c. connection.
4. In addition to the concentric capacitive connection of the shield to the shell, the prototype connector also had a ferrite bead around pin 1 and ribbed construction of the shell designed to improve connection of the shield with the mating connector. The authors believe that in addition to providing an effective cure for the pin 1 problem, this construction improves shielding at UHF.
5. It is possible to build excellent immunity into a microphone when connecting the shield only to pin 1. Microphone DS1, a very highly regarded product, does that.
6. Of the 36 microphones tested, more than one third provided complete immunity to all of the generators when the concentric capacitor was used to terminate the shield, and half performed at very nearly to level.
7. In light of items 1-6 above, there is no justification for making a d.c. connection of the shield of XL cables to the shell of a cable-mounted connector. Such a connection can cause serious EMC problems when such a cable is used in many permanently installed systems.
8. Cables connecting vacuum tube microphones with a power supply should be fitted with connectors having concentric capacitive termination of the shield to the connector shell.
9. The measures required to eliminate susceptibility in the tested microphone are simple and inexpensive. Current products require little more than proper termination of the cable shield, attention to internal grounding, a few ferrite beads, and a few well chosen and well placed capacitors.

10 The screw connecting the XL connector to the body of the microphone does not provide an adequate connection for the cable shield at UHF.

11. Handheld transceivers are an effective engineering tool in the evaluation of the RF susceptibility of audio systems in general and condenser microphones in particular.
12. Microphones tend to remain in use for decades. The connector with the concentric capacitor can allow many vintage microphones having pin 1 problems to provide decades of use in ever more demanding EMC environments without modification of the microphones.
13. The output stages and shielding schemes of microphones having poor immunity should be redesigned.
14. Serious attention should be paid to improving the generally poor immunity of microphones having extension cables to capsules that are remotely located from their line driver.
15. MF sources should not be ignored. Shield current-induced-noise in microphone cables will convert the signals from nearby AM broadcast transmitters into differential mode voltages on the signal pair. It is therefore critical that the bandwidths of microphone circuits be limited to the minimum required to provide good magnitude and phase response within the audio spectrum. In no case should the bandwidth of a microphone intended for other than scientific purposes extend above 200 kHz.

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Waldron for making sure we knew what microphones most needed testing; to Bill Whitlock, Bruce Olson, and Dr. Rachelle Weiss for their review of the manuscript, and especially to Neil Muncy for first alerting our industry to "the pin 1 problem."

DISCLAIMER

While author Brown believes he was the first to propose the use of a capacitance having essentially concentric geometry within a cable-mounted XL connector to terminate the shield of balanced audio wiring, he has no business relationship with any potential manufacturer of such a connector.

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