# Investigation of Cavity Resonances in an Automobile

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*Abstract*—**Knowledge of cavity resonance within the automobile is needed to predict electromagnetic crosstalk between circuits in vehicle cavities. To quantify potential cavity resonances, resonance was studied within the passenger compartment of a standard automobile. Measured values of $S_{11}$, $S_{21}$ and Q (quality factor) are presented and their effect on crosstalk is discussed. Resonances were found at frequencies from 72 MHz to 303 MHz with quality factors ranging from 4 to 40.**

***Keywords- coupling; crosstalk; cable routing; automotive EMC; electromagnetics***

## I. INTRODUCTION

Theoretical equations exist that allow one to calculate crosstalk between two circuits [1, 2]. These equations are typically effective when applied in a simple environment, for example when two wires are run parallel to one another over a ground plane. However, when confined within a resonant cavity, the crosstalk between these circuits can change considerably from the simple case. Factors considered in the typical set of equations, for example distance between the circuits, may no longer play a significant role. Complex numerical models could be used instead to predict crosstalk, but require significant setup and simulation time and do not give an intuitive feel for the interactions that cause a particular result.

Accurately predicting crosstalk using simple equations requires some knowledge of the potential resonances that may exist within cavities created by body-surface metal and other metal components that define the system. To quantify potential resonances within the automobile, experiments were performed to measure resonances within the passenger compartment of an example vehicle. Cavity resonances were explored by making measurements of scattering parameters $S_{11}$, $S_{22}$, $S_{21}$ and $S_{12}$ among antennas placed in the passenger compartment. Four different measurements were made. Measurements were first performed without any modifications to the passenger compartment. Windows and doors were then covered with aluminum foil or copper tape and the measurements were performed again, to allow better detection of resonances caused by the cavity as opposed to the antennas or vehicle-body. When comparing measurements with and without aluminum foil covering the windows, peaks in $S_{11}$ and $S_{22}$ caused by the antennas should remain approximately the same, while peaks caused by cavity resonances should increase. Measurements were also made with the antennas reversed to protrude into the room rather than into the cavity. These measurements were performed to further demonstrate that resonances originated within the passenger compartment and not from the measurement equipment or from the body-surface metal serving as a counterpoise for the antennas. Finally, measurements of inductive and capacitive coupling in the passenger compartment were made and compared with the coupling that would be expected in free space.

## II. CAVITY RESONANCE MEASUREMENT

### A. Exprimental Setup

The car used for this study was a late-model 4-door luxury sedan. The experimental setup is shown in Fig's 1 and 2. Four holes were drilled in the car, three on top of the car and one in the driver-side door. Paint was removed from the body-surface around these holes. A monopole antenna was placed through each hole into the passenger compartment. The antennas were marked 1, 2, 3, and 4 as shown in Fig. 2. The length of the antennas varied. Antenna 1 was 20 cm long, antenna 2 was 10 cm long, antenna 3 was 20 cm long, and antenna 4 was 5 cm long. Each antenna was placed approximately perpendicular to the body-surface metal. The antennas were connected individually or in sets of two to a HP 8375 network analyzer using a 50-Ω SMA coaxial cable. The cable shields were electrically referenced to body-surface metal using copper tape.

Fig. 1. Experimental setup. Cavity resonances were measured with a network analyzer using antennas placed into the passenger compartment.

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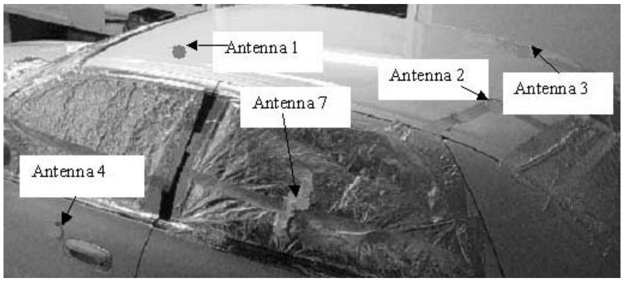


Fig. 2. Measurements of resonances in the passenger compartment were made with aluminum foil covering the windows and attached capacitively to the body-surface metal. Antennas were later reversed to compare cavity measurements against the response of the room.

Values of the reflection coefficients, $S_{11}$ and $S_{22}$, and transmission coefficients, $S_{21}$ and $S_{12}$, were measured using the network analyzer. $S_{11}$ and $S_{22}$ can be used to find the efficiency of energy transfer to the cavity, an indicator of resonance. $S_{21}$ and $S_{12}$ are similarly related to the energy transfer between two antennas in the cavity. The quality factors, Q, of any peaks in $S_{11}/S_{21}$ were calculated as the ratio of the resonant frequency to the half-power bandwidth of the peak [3-5].

### B. *Measurement results*

Fig. 3 shows the power delivered by antenna 4 into the passenger compartment. The thin curve shows the values measured in the un-altered compartment (without aluminum foil covering the windows). The thick curve shows the values measured when the windows were covered with aluminum foil. Similar plots were made for the other antennas. Several observations can be made regarding these measurements.

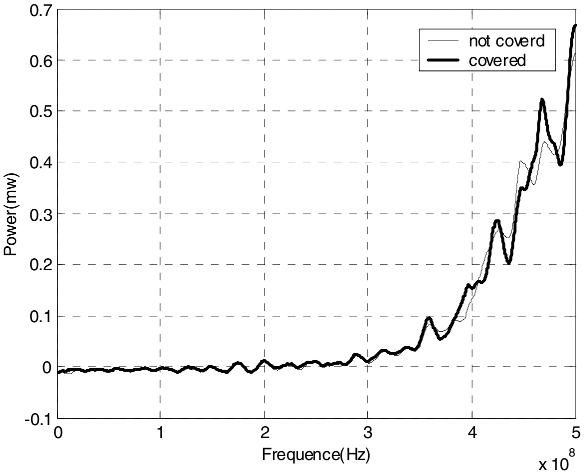


Fig. 3. Power delivered into the passenger compartment by antenna 4 when the windows were and were not covered with aluminum foil.

When aluminum foil is placed over the windows, local peaks in power delivery are generally enhanced. Some additional peaks occur, perhaps because resonances at those frequencies are also enhanced or because the aluminum foil changes the cavity sufficiently to introduce new resonant modes. The increase in Q (the "sharpening" of power delivery peaks) when the windows are covered with aluminum foil indicate the measured resonances are caused within the cavity and not by the measurement setup.

In general, local peaks in the power delivery curve are small, indicating low values of Q in the passenger compartment. This result is not surprising due to the variety of "loads" within the compartment. Because the peaks are small (perhaps less than a 3dB change), it is difficult to calculate the values of Q strictly from $S_{11}$ itself. Measurements of $S_{21}$ are needed because they are likely to be more sensitive to cavity resonances.

Fig. 4 shows measured values of $S_{21}$ between antennas 2 and 3 within the passenger compartment. The thick, solid curve shows the values measured in the un-altered compartment. The thin black line shows the values measured when the windows were covered with aluminum foil. Resonances were found at 74 MHz (Q=15), 99 MHz (Q=18), 191 MHz (Q=14), and 220 MHz (Q=14). Resonances found in the unaltered compartment were generally enhanced (i.e. Q increased) when the windows were covered with aluminum foil, indicating that they were due to cavity resonances in the passenger-compartment and not some other source.

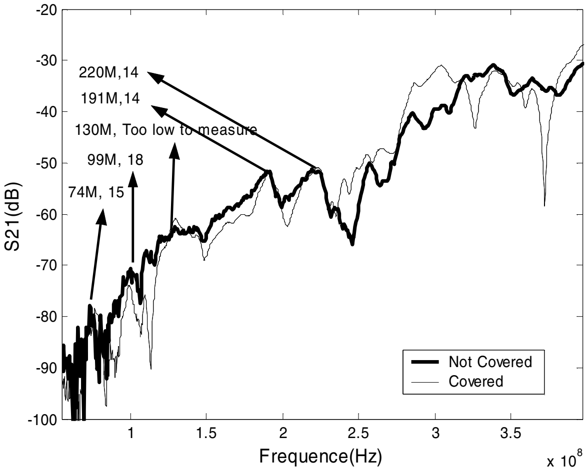


Fig. 4. Values of $S_{21}$ measured between antennas 2 and 3 when the windows were and were not covered with aluminum foil. Values are given for peaks measured when the car was not covered with aluminum foil.

Fig's 5-6 compare measured values of $S_{21}$ when the antennas were pointed into the passenger compartment and when they were reversed into the room. The numbers in the figure show the resonant frequencies and their Q for each peak when the antennas were in the passenger compartment and the windows were covered with aluminum foil. With few exceptions, peaks found in $S_{21}$ in the passenger compartment were not present when the antennas were reversed,.

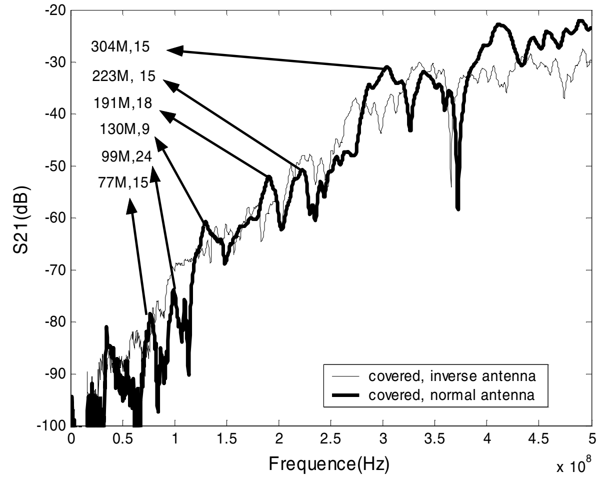


Fig. 5. Values of $S_{21}$ measured between antennas 2 and 3 when the antennas were in the passenger compartment and when they were reversed into the room.

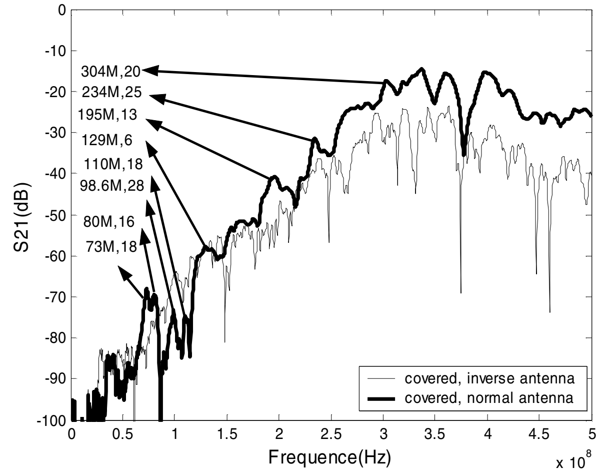


Fig. 6. Values of $S_{21}$ measured between antennas 2 and 7 when the antennas were in the passenger compartment and when they were reversed into the room.

The cavity resonance frequencies and their quality factors as determined by the measurements are summarized in Table 1. The antenna columns are marked such that "23" indicates resonance measured in $S_{21}$ between antennas 2 and 3. "Covered" indicates windows were covered with aluminum foil; otherwise, windows were not covered. From this information, we can conclude that:

- Relatively low-frequency (from 72 MHz to 303 MHz) resonant modes can be excited in the passenger compartment, though there is sufficient damping within the cavity that the Q of those modes is small (ranging from approximately 4 to 40).
- Antennas at different positions excite different resonant modes.

Covering the windows with aluminum foil generally results in resonances at the same frequencies with an increased Q.

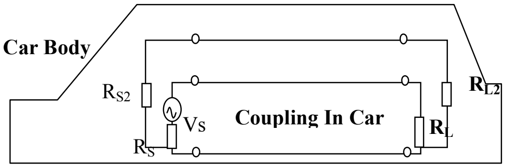
Table 1. Quality factors for resonant frequencies found in the passenger compartment.

| Antennas<br>Frequency | 12 | 12 Covered | 13 | 13 Covered | 23 | 23 Covered |
|---|---|---|---|---|---|---|
| 72 | **7** | **22** | **4** | **18** | | |
| 77 | | | | | **15** | **15** |
| 80 | | | **4** | **9** | | |
| 83 | | | | | | |
| 88 | **8** | **12** | | | | |
| 99 | | | | | **18** | **24** |
| 110 | | | | | | |
| 127.5 | | | **7** | **7** | | |
| 130 | **9** | **13** | | | | **9** |
| 186 | | | | | | |
| 191 | | | | | **14** | **18** |
| 195 | | | | | | |
| 198 | | | | | | |
| 201 | | | **12** | **10** | | |
| 223 | | | | | **14** | **15** |
| 235 | **10** | **16** | | | | |
| 238 | | | | | | |
| 264 | | | | **9** | | |
| 287 | | **17** | | | | |
| 303 | | **45** | **5** | **40** | | **15** |

## III. EFFECT OF CAVITY RESONANCE ON CROSSTALK

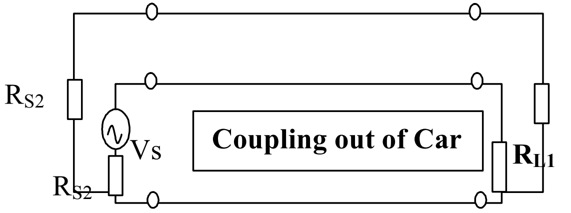
Once resonance in the passenger compartment was characterized, its effect on crosstalk was studied. This study was performed to show when resonances in the passenger compartment should be included in crosstalk calculations based on simple coupling equations. Crosstalk was studied in cable harnesses that transversed the passenger compartment from the front to back along the doors and in harnesses that transversed the passenger compartment from left to right beneath the back seat. Experimental results were compared to simulations and to the coupling predicted in free space.

The experimental setup is shown in Fig. 7. A representative pair of circuits was created for the experiments. For one set of circuits, the culprit and victim circuits were relatively close (2 mm) and in another they were far apart (85 cm). Coupling between the circuits was measured first in free space and then with the circuits in the passenger compartment. Measurements were compared to indicate the effects of cavity resonance, if any, on crosstalk.



**Measurement In Car**

(a)



**Measurement In Free Space**

(b)

Fig. 7. Experimental setup to show effect of cavity resonances on crosstalk.

### *A. Circuits close to one another*

Fig's 8-9 show the measured value of coupling between two circuits when the culprit and the victim circuit were 2 mm apart. In Fig. 8, capacitive coupling dominates. In Fig. 9, inductive coupling dominates. Values of crosstalk calculated using lumped-element models are also shown. The differences between the measurements made in free space and in the car were small, indicating that the cavity resonance had a negligible effect on crosstalk between circuits that share the same harness.

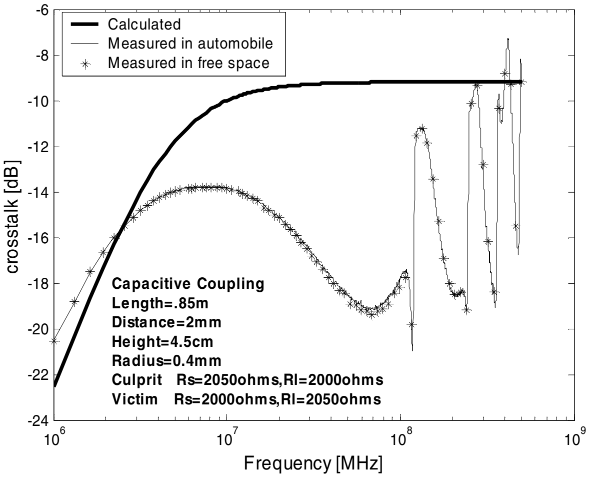


Fig. 8. Comparison of capacitive crosstalk measurements in the passenger compartment to measurements in free space and to values calculated using a lumped-element model.

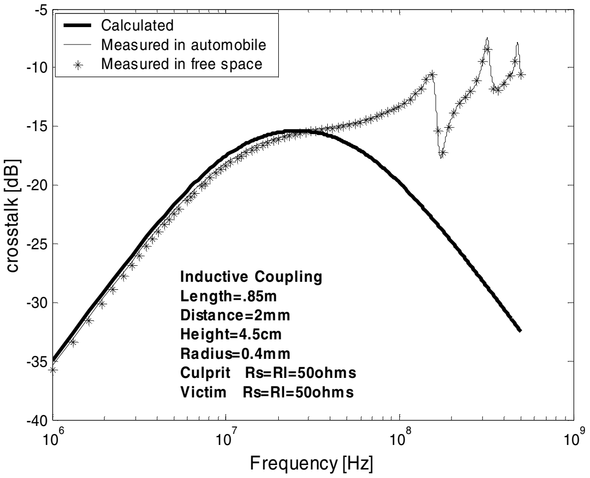


Fig. 9. Comparison of inductive crosstalk measurements in the passenger compartment to measurements in free space and to values calculated using a lumped-element model..

### *B. Circuits far apart*

Fig. 10 shows the measured value of coupling between two circuits separated by 85 cm. Peaks in coupling occurred at the resonance frequencies that were identified in the earlier measurements. However, the coupling was relatively small (less than -50 dB in this case).

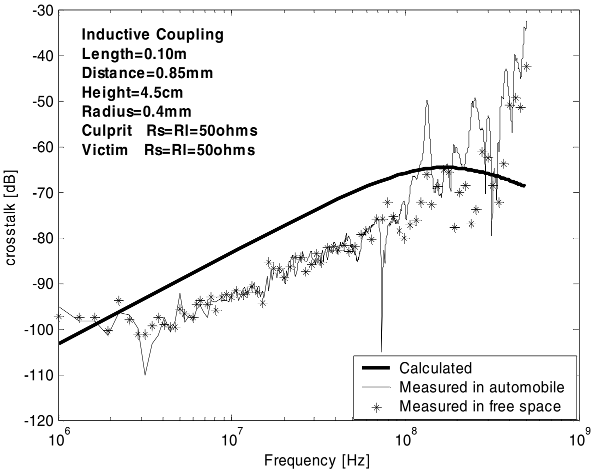


Fig. 10. Comparison of inductive crosstalk measurements in the passenger compartment to measurements in free space and to values calculated using a lumped-element model. The culprit and victim circuits were 85 cm apart.

## IV. DISCUSSION AND CONCLUSIONS

Resonances were found in the passenger compartment of an example vehicle for frequencies as low as 72MHz. Assuming the passenger compartment was an empty rectangular metal box with dimensions 3m x 1.5m x 1.2m, theory suggests the first cavity resonance should not occur below 112MHz [3, 4, 5, 6]. This low-frequency resonance may occur because of metal objects within the passenger compartment. These metal components, both referenced and floating relative to the enclosure, might cause resonant modes other than the TE and TM modes that exist in an empty cavity.

Resonance was explored using both $S_{11}$ and $S_{21}$. While $S_{11}$ may give more accurate values of the Q within the cavity, $S_{11}$ proved to be a poor tool for making measurements in a low-Q structure like the automobile. Better results were obtained using $S_{21}$, though exact values of Q may be over- or under-estimated, depending on the joint characteristics and placement of the antennas. Because values of Q were small, several methods were used to guarantee that the measured resonances were cavity resonances of the passenger compartment and not an artifact of the measurement setup. The results suggest that our final measurements accurately reflect what is happening in the passenger compartment.

To complete this study, measurements were made to determine the effect of passenger compartment resonances on the crosstalk between circuits in the automobile. Results indicated that the values of Q were relatively small (4-40) for the passenger compartment and that resonance only played a significant role when the culprit and victim circuits were far apart and coupling was weak. This suggests that most crosstalk calculations in the passenger compartment may be made using simple calculations that ignore the characteristics of the cavity, except when operating at very high frequencies or when coupling is weak.

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