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Environmental Contamination Effects on External Automotive Microphones: An Experimental Study

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ABSTRACT

Weatherproofing or ingress protection (IP) is an important reliability requirement for microphone designs. The most common microphone weatherproofing approach is to cover the acoustic porthole with an acoustically transparent mesh layer. This approach is usually effective to protect the microphone from typical dust and water damages but may not prevent the microphone performance such as frequency response (FR) from shifting away from the default behavior. For microphones used in external environments, especially the exterior of a vehicle, there are higher risks of FR characteristics shifting due to foreign object contaminations. Changes in FR characteristics often degrade the performance of microphone dependent applications or even prevent them from functioning completely. To understand how FR could change when being contaminated, microphone samples of three design types are tested under contamination conditions possibly encountered during vehicle operations, including water and moisture, dry sand and dust, and wet mud. The three microphone types come with different weatherproof design features, such as treating the porthole with acoustic meshes or structurally sealing the entire housing. It is shown that, among different contamination conditions considered in this study, dry dust/sand presents minimal influences on microphone responses, followed by water/moisture, then wet mud causing the most significant impact. Furthermore, it is also demonstrated that, for non-sealed microphones regardless how the porthole is protected with mesh layers, there is always a chance for foreign objects (e.g., water, dust, mud) to migrate into the microphone thus significantly change the microphone performance.

1 Introduction

Protecting enclosures against foreign object like dust and moisture intrusion, known as Ingress Protection (IP) or generally referred to as weatherproofing, is a crucial requirement ensuring the environmental reliability and longevity of electrical devices. The level of IP ratings is typically dictated by two international standards – the IEC standard 60529 and the ISO standard 20653 [1, 2]. The protection level definitions are generally similar in these two standards, but with minor differences in testing requirements. Among the two, the IEC 60529 standard is used for general consumer and industrial electrical equipment (e.g., smartphone, laptop, camera), while the ISO 20653 standard is specifically tailored for equipment mounted on road vehicles. Standard IP ratings consist of the letters "IP" followed by two digits. The first and the second digit indicates the protection level against solid foreign particle ingress (e.g., dust) and various forms of moisture (e.g., water) ingress, respectively. The higher the number, the better the protection thus higher environmental reliability. For example, smartphones with an IP67 or IP68 rating mean that they are dust-tight (first digit 6) and can withstand temporary immersion in water (second digit 7) or

continuous immersion (second digit 8). Following the ISO 20653 standard, the highest IP requirement for equipment used in road vehicles is IP6K9K, which means that it is dust-tight (6K) and can withstand high-pressure high-temperature steam jet cleaning (9K). The letter "K" simply indicates specific testing conditions relevant to road vehicles.

To meet high level IP ratings such as IP6K9K, an enclosure almost needs to be effectively sealed from the environment. Obviously, this is a very challenging task for microphones since they rely on a direct airpath (i.e., the porthole in a microphone element or microphone module) to expose the sound sensing membrane to the environment to properly pick up air-borne sound signals. Any types of foreign object contamination including obstruction in the direct airpath may change the microphone behaviour such as its sensitivity and frequency response (FR), leading to application issues.

The most common microphone weatherproofing approach is to cover the porthole with a porous mesh layer that are often considered acoustically transparent [3]. This approach is usually effective to prevent excessive amount of dust and water from entering the microphone porthole, thus protecting the delicate membrane and circuit components inside the microphone package from being damaged. But it may not prevent the microphone performance from drifting away from its intended specifications over usage since water or dust buildup could change the acoustic transparency property of the mesh layer. On the other hand, when validating microphone against standard IP ratings, the passing criterion is typically the microphone performance (e.g., FR) staying within a pre-determined tolerance after being undergone relevant IP tests. If the post-test performance measurement is not made immediately after the IP test, the exact contamination status can disappear over time (e.g., dust falling off and water drying out). Therefore, the IP ratings of a microphone may only indicate that the microphone can function properly (i.e., within the performance tolerance) after the relevant dust and moisture contamination conditions are stopped or removed (e.g., by cleaning); it does not necessarily mean that performance variations are always acceptable while the contamination conditions still present.

Microphone performance variations due to foreign object contamination can be considered as specification mismatch or deviation from a reference state, e.g., the datasheet specification. Impacts of microphone performance mismatch have been mostly studied for beamforming applications in the literature [4-7].

In an earlier study on effects of microphone mismatch in directional hearing instruments, it was found that dirt and debris accumulation over time in the acoustic pathway affected the directivity. After about one year usage, the noise rejection performance measured by a "front-to-back" ratio exhibited 2-8 dB degradation on average between 100 and 8k Hz [4]. Microphone FR mismatch, represented by gain and phase errors, can affect array performance to various degrees depending on the array designs [5-7]. When evaluated in terms of the array SNR (Signal to Noise Ratio), a ±3 dB gain error between individual microphone channels led to a relatively small degradation (<1 dB) for a 2-element array. But the SNR degradation was up to 4 dB for a 6-element array [5]. In the latter case, the expected SNR improvement associated with the 6-element array was reduced by nearly 50% due to the ±3 dB gain error. In a recent study, Du et al. simulated gain and phase mismatch effects based on a 4-element array design. Similar to Ref. [5], they showed that, with mismatch up to ±3 dB in gain and ±45º in phase, the array SNR change was less than 1 dB when using the simple delay-and-sum algorithm [6]. However, the SNR degradation could be more than 10 dB when the more advanced minimum variance distortionless response (MVDR) algorithm was used. Furthermore, existing results also demonstrated that microphone performance mismatch could cause more negative effects on array performance as frequency decreases [7].

In addition to the question of how microphone performance mismatch could affect application such as array performance, another relevant question is to what extent microphone performance could drift under practical use conditions. In Ref. [8], the FR of a recording microphone was measured with dry and wet foam covers. It was demonstrated that the FR amplitude changed significantly above 2 kHz when the foam cover was soaked. Even when the water trapped in the foam cover was squeezed out and dried for an additional half an hour, noticeable FR amplitude change could still be observed. This type of data is critical toward understanding actual microphone performance drifting and its effects on end applications, especially for microphones used in external environments like the exterior of a vehicle.

As vehicles could be driven under all kinds of road and weather conditions, microphones mounted on the

exterior of a vehicle are expected to not only survive but also function properly in both wet-dry weather and on clean-dirty road. Thus, in addition to IP rating requirements, it is important to understand how performance could drift during and after a microphone is being contaminated by weather and road hazards.

Attempting to answer this question, we tested automotive microphone samples of three design types, each with a different weatherproof design strategy. The first microphone type is weatherproofed by covering the porthole with an acoustic mesh layer, the second type adds a dedicated mechanical feature in addition to the acoustic mesh layer to help divert foreign objects away from the porthole, and the third type uses a solid membrane to structurally seal the entire microphone housing. Considering possible vehicle operation environments, we selected four contamination test conditions: water spray, water immersion, dry sand and dust, and wet mud.

Section 2 in this paper presents a simple lumped parameter model to simulate how microphone FR characteristics could change due to parameter variations of the acoustic pathway. Experimental methods for FR measurements under different contamination conditions are explained in Section 3. Section 4 presents experimental results and relevant discussions. Finally, Section 5 summarizes the findings and future work.

2 Simulations

Based on a lumped parameter microphone model developed in [9], a simple circuit model for simulating foreign object contamination effects on microphone FR is illustrated in Fig. 1. In this model, the sound source is given as a constant voltage source. Sound waves enter the microphone then impinge on the sound sensing membrane through the acoustic porthole that is represented by a lumped mass term (inductor L_{port}) and a lumped damping term (resistor R_{port}). Capacitor C_v in the left-side branch of the circuit represents the acoustic compliance associated with the air volume between the porthole and the membrane. All other electroacoustic properties of the microphone including the acoustical to mechanical and mechanical to electrical transductions are lumped into an overall impedance term (Z_{mic}) in the right-side branch of the circuit. The FR of the microphone is then obtained by calculating the transfer function between the voltage output measured at the "Out" terminal and the input due to the voltage source.

For protection, microphone portholes are typically covered with acoustic grille, foam or mesh layers by design. During usage, foreign object contaminations like water and debris can accumulate on or be trapped within pores and small air gaps in those protection layers, effectively changing (usually adding) the mass and damping of the porthole. Figure 2 plots the microphone FR when L_{port} and R_{port} in the circuit model are increased up to 10 and 20 times of their original values, respectively. It is seen that FR changes occur mainly in the high frequency region. With added damping the FR amplitude around the resonance frequency is attenuated, while added mass shifts the resonance toward lower frequencies.

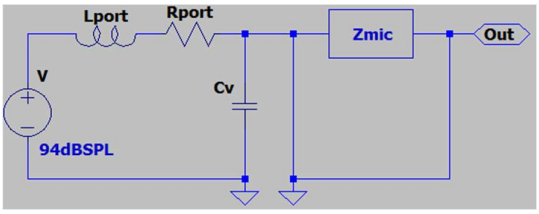


Fig. 1. Microphone lumped parameter model.

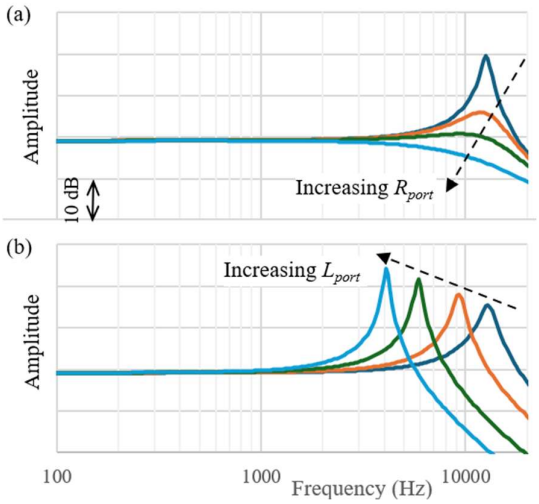


Fig. 2. Simulated amplitude FR changes due to variations in effective acoustic port (a) damping and (b) mass.

It should be noted that the simulation model in Fig. 1 only considers situations where the microphone porthole acoustic properties are altered due to foreign object covering or clogging the air pathway. When water or debris penetrate the protecting grille, foam

or mesh layer reaching the membrane, parameters C_v and Z_{mic} could also be affected, resulting in more complex FR behaviour than those shown in Fig. 2. Nevertheless, the results in Fig. 2 provide a guidance for what may be expected in practice and help to explain experimental results.

3 Experimental Methods

In the experimental study, the microphone FR was measured and compared to show the environmental contamination effects. Three types of microphone designs for automotive applications and four contamination test conditions commonly encountered by vehicles were used.

3.1 Contamination test conditions

Four environmental contamination test conditions were selected and referred to as (1) water spray, (2) water immersion, (3) dry sand and dust, and (4) wet mud in this study. The water spray and immersion conditions intended to simulate driving situations in light to heavy rain, respectively. The dry sand and dust condition could happen when driving on dry unpaved roads. And the wet mud condition considered situations like driving on dirty roads after rain or snow.

For the water spray condition, the microphone under test (MUT) was placed on a table with its front surface (i.e., the grille, shell or structural membrane) facing upward. Clean tap water was sprayed onto the MUT from a spray bottle positioned about 20 cm above the MUT, until the front surface of the MUT was lightly damped. In contrast in the water immersion test, the MUT was submerged under 1 m deep clean tap water continuously for 60 minutes.

Under the dry sand and dust condition, a mixture of approximately 4.5 parts (in volume) cement powder to 4.5 parts drywall powder to 1 part play sand was formed that contained particles as small as 10 um to above 100 um in diameter. The MUT was then mixed with the sand and dust mixture in a jewelry tumbler continuously for 10 minutes.

For the wet mud condition, 7 parts (in volume) potting soil to 3 parts drywall powder were blended with water to achieve the soggy mud mixture. The MUT was dipped into and gently shaken by hand inside the mud puddle with its front surface (i.e., the grille, shell or structural membrane) facing down for about 1 minute.

For reference, Fig. 3 shows how foreign object could contaminate different MUTs immediately after the contamination tests as described above were completed. Note that the test condition of water immersion is not included since the MUT looked very much like the water spray case by the appearance. Microphone types called out in Fig. 3 are explained in the next section.

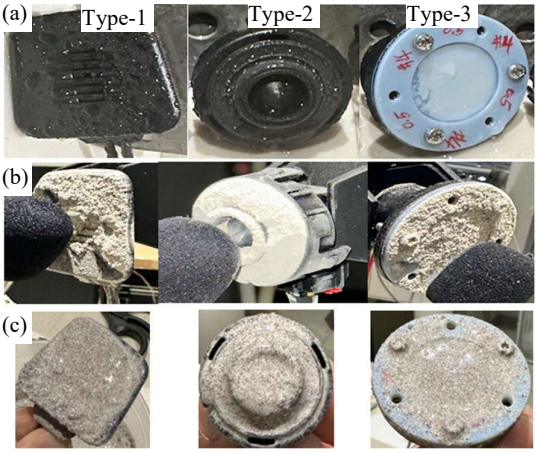


Fig. 3. DUT appearance immediately after contamination test of (a) water spray (and water immersion), (b) dry sand and dust, and (c) wet mud.

3.2 Microphone types

Three microphone types with different design features for ingress protection are shown in Fig. 4. Type-1 microphone uses a face grille to cover and structurally protect the microphone element underneath. The gap opening in the grille is about 2 mm in width that is typically too large to prevent small size foreign objects such as water and debris from going through. Therefore, an acoustic mesh layer with a fine pore size is used to cover the microphone porthole (not visible in the picture) under the grille. The acoustic mesh layer serves as the main ingress protection mechanism for Type-1 microphone.

Type-2 microphone design also uses an acoustic mesh layer to cover the porthole for water and debris protection. Instead of the face grille, the Type-2 design uses a cone shaped shell structure; a narrow air gap less than 1 mm in width is cut along the edge of the shell (white circle in Fig. 4b) to allow sound waves to pass through. By covering the microphone element with the cone shaped shell, a detoured

pathway is created between the environment and the porthole. Thus, water and debris can be more effectively blocked or diverted away from entering the microphone porthole.

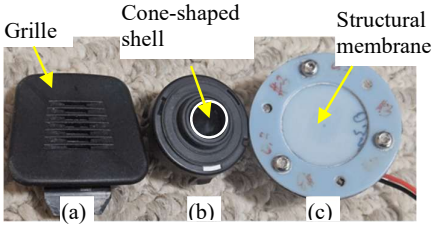


Fig. 4. Microphones under test of (a) Type-1, (b) Type-2 and (c) Type-3 designs.

Different from Type-1 and Type-2, Type-3 microphone does not cover the microphone element with a mesh layer, it seals the microphone element with a solid structural membrane. The structural membrane is flexible enough to allow sound transmission while also structurally strong enough to act as part of the microphone protective housing. Since the Type-3 design removes the direct airpath connecting the external environment to the acoustic sensing element, theoretically no foreign objects can reach and contaminate the microphone sensing element.

To isolate the effects of different environmental contamination conditions, four samples of Type-1 and Type-2 microphones were used, each for a separate contamination condition. For the Type-3 microphone, ideally a single sample could be used for all four contamination conditions since Type-3 design had a sealed housing and was perfectly cleanable after each contamination test. During testing, it was found out that the first Type-3 microphone sample was accidentally damaged due to mishandling after the water spray test (but was not because of the water spray itself). Therefore, a second Type-3 microphone sample was used for the remaining three contamination tests. It should be pointed out that, due to sample limitations, the two microphone samples of the Type-3 design available to this study had slightly different FR in the high frequency range. However, this did not affect this study as the discussions and analyses were based on the FR changes before versus after the contamination tests for each individual MUT.

3.3 Measurement steps

Before each contamination condition was applied, the FR of each MUT was measured and saved as the reference pretest curve (FR0). A first post-test FR measurement (FR1) was always made immediately following each contamination test condition (see description in Section 3.1). Multiple measurements were then carried out at different times following the contamination test, which are listed in Table 1.

In Table 1, the process "drying" means that the MUT was placed in a well-ventilated room under temperature at about 25 ºC and being air dried for the specified duration. After 24 hours, the MUT was basically completely dried. The process "cleaning" involved carefully removing sand, dust or mud from each MUT to restore its pretest appearance.

Contamination test 1 – Water spray	
FR1	0-min after
FR2	After 24-hour drying
Contamination test 2 – 1 m Water immersion	
FR1	0-min after
FR2	After 15-min drying
FR3	After 45-min drying
FR4	After 24-hour drying
Contamination test 3 – Dry sand and dust	
FR1	0-min after
FR2	After cleaning
Contamination test 4 – Wet mud	
FR1	0-min after
FR2	10-min after
FR3	After 24-hour drying
FR4	After cleaning (with wet cloth) and additional 24-hour drying

Table 1. FR measurement steps.

4 Experimental Results

To show the performance changes, the FR of each MUT was measured before and at different times after each of the four environmental contamination tests. The measured FRs of each MUT are normalized to its pretest sensitivity at 1 kHz and compared in Figs. 5-8. From the pretest FR results, it is seen that the three types of microphone samples have distinct FR shapes. This is especially true at higher frequencies where acoustic resonances and anti-resonances may occur corresponding to specific structural features associated with each individual design. As mentioned previously, the focus of this study is how the FR of the same MUT may change before and after different environmental

contamination tests, the inherent (i.e., pretest) differences in FR shapes do not affect the analysis and discussion in this study.

Figure 5 shows the results for the water spray test case. It is seen that when measured immediately following the water test (FR1 curve), only the Type-2 sample presented small changes in the high frequency range above 5 kHz. No FR change is observable for Type-1 and Type 3 samples. After 24 hours drying, the FRs of all test samples basically are the same as their pre-test results. This indicates that changes in FR behaviour due to lightly damped condition (e.g., by the sprayed water) is minimum to none when the microphone porthole is either covered by a breathable acoustic mesh layer (Type-1), by a shell structure in additional to a mesh layer (Type 2) or sealed by a solid membrane (Type-3).

When submerged under water for some time, relatively large amount of water could accumulate on or even penetrate through the mesh layer, causing changes in the acoustic properties of the airpath directly in front of the microphone porthole, thus the FR behaviour as well. This is demonstrated in Figs. 6a and 6b for the 1-meter water immersion, in which both microphone Type-1 and Type-2 exhibit significantly different FR shapes immediately post the water immersion (blue solid lines). Compared to their pretest curves, the resonances of microphone Type-1 and Type-2 are shifted to a much lower frequency and the amplitudes are significantly attenuated above the resonance frequency. This phenomenon is similar to what is shown by the simulation model in Fig. 2. It implies that when the water accumulation around the acoustic opening is large enough, the water buildup acts as added mass and damping to the acoustic path.

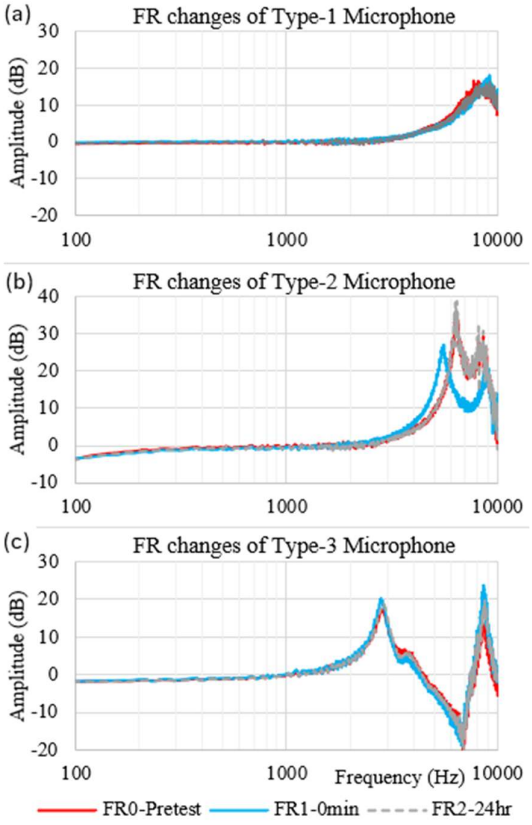


Fig. 5. Comparison of normalized FR for microphone (a) Type-1, (b) Type (2), and (c) Type-3 before and at different times after water spray test.

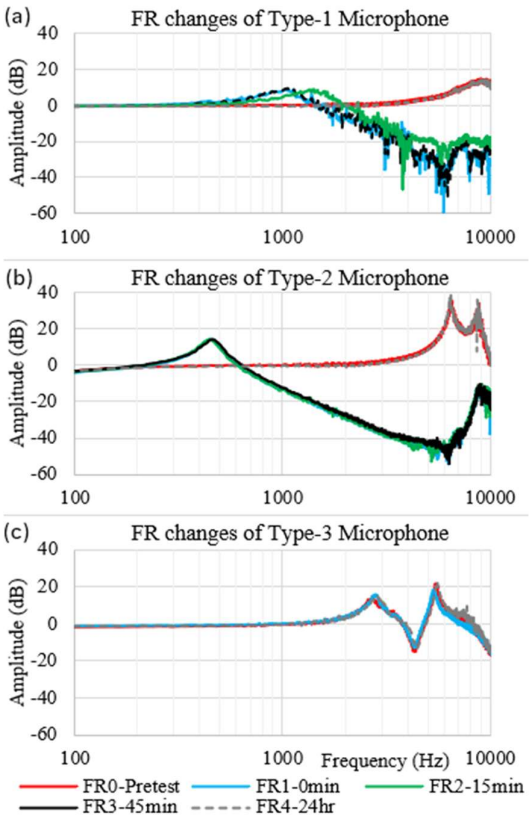


Fig. 6. Comparison of normalized FR for microphone (a) Type-1, (b) Type (2), and (c) Type-3 before and at different times after water immersion test.

It is also interesting to notice from Figs. 6a and 6b that although the water effect can last an extended period of time (at least > 45 minutes), the FRs of both microphone Type-1 and Type-2 recovered to the pretest status after drying for 24 hours when the MUT was completely dry again. In contrast, performance of microphone Type-3 stays the same all the time. This is not surprising as Type-3 design seals the microphone porthole with the structural membrane, which basically removes the possibility of water accumulating around or entering the porthole.

In Fig. 7, the pretest FR results are compared to two measurements post the dry sand and dust test case. The first post-test measurement was made when loose sand and dust were still stuck to the surface of the test samples (Fig. 3b). Then after carefully shaking and wiping (with dry cloth) off the sand and dust, a second FR measurement was made. Similar to what was shown after the water immersion test, results in Fig. 7 show that microphone Type-3 performance is not affected by dry sand and dust. However, the FR resonances of microphones Type-1 and Type-2 are substantially attenuated while the resonance locations do not change much. According to the circuit simulation model, sand and dust accumulation around the acoustic opening primarily acts as added damping to the acoustic path. It is also worth to point out that the sand and dust influence seems to be more significant for microphone Type-1 then for Type-2. FR amplitude of microphone Type-1 is attenuated at all frequencies, while attenuation is only observed at high frequencies around the resonance area for microphone Type-2. After cleaning, all microphones recovered to the same performance as shown by the pretest curves

Finally, Fig. 8 shows the results for the wet mud test case. When the mud mixture was wet and sticky, it stayed on the microphone surfaces and changed the FR behaviour of all microphone design types. This can be seen from the FR results measured at 0 and 10 minutes after the mud test. For microphone Type-1 and Type-2, the wet mud acts again as added mass and damping to the acoustic pathway, which results in FR changes in a wide frequency range and up to 40 dB in amplitude. The wet mud appears to affect microphone Type-3 to a lesser extent in terms of amplitude changes in general, but the first response resonance does shift significantly from close to 3 kHz to around 1.5 kHz due mostly to the added mass effect to the structural membrane.

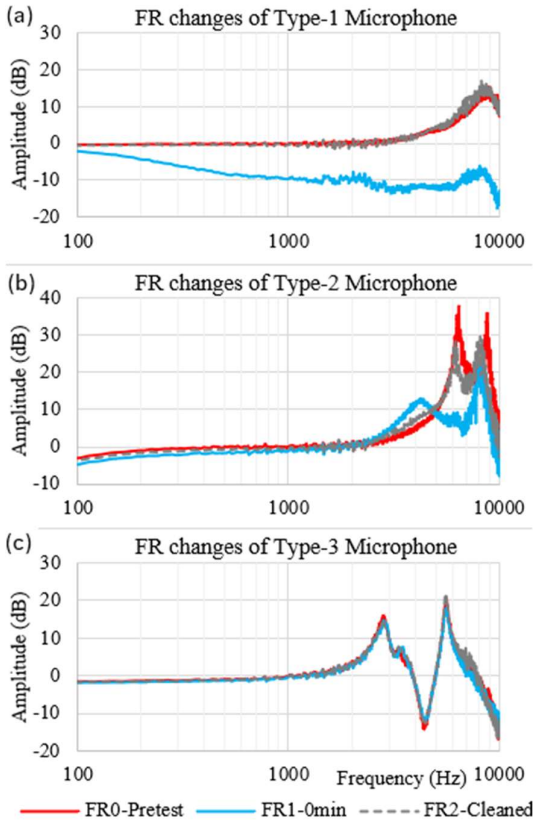


Fig. 7. Comparison of normalized FR for microphone (a) Type-1, (b) Type (2), and (c) Type-3 before and at different times after sand and dust test.

After drying for 24 hours, the residue mud became dry and formed a hard shell covering the acoustic openings of microphones Type-1 and Type-2, and the structural membrane of Type-3. Under this situation, microphone Type-1 FR does not see appreciable improvement compared to the wet mud status, while microphone Type-2 FR becomes much closer to the pretest shape. This observation may be explained by examining how the acoustic portholes are protected by microphone Type-1 and Type-2 designs. Microphone Type-1 uses an acoustic mesh layer to cover the porthole, mud mixture regardless of wet or dry covers the mesh layer directly and leads to similar added mass and damping effects to the acoustic pathway. Type-2 design has an additional cone-shaped structural shell in front of the mesh layer. This structural shell helps block solid contents in wet mud from reaching the mesh layer. When dried, the effect of water on the acoustic characteristics of the air pathway is substantially removed, thus the FR shape is closer to the pretest curve again.

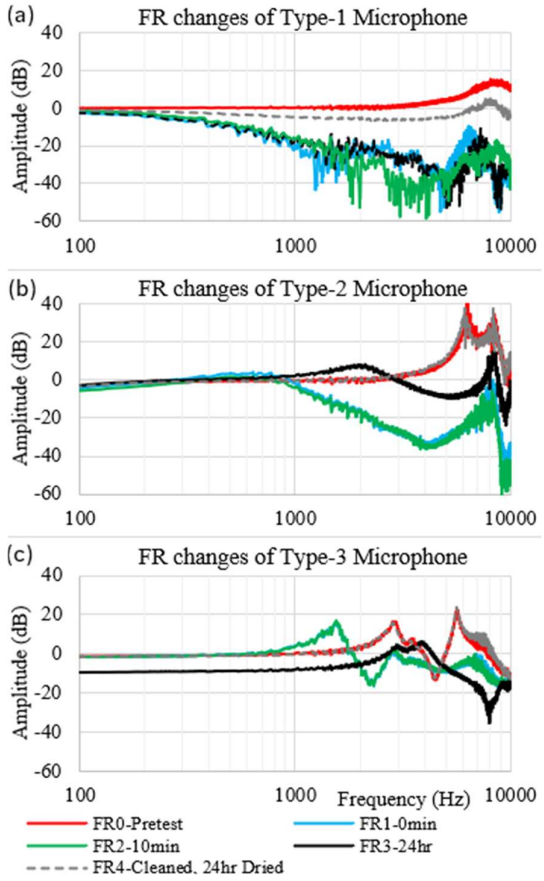


Fig. 8. Comparison of normalized FR for microphone (a) Type-1, (b) Type (2), and (c) Type-3 before and at different times after wet mud test.

Different from both Type-1 and Type-2 microphones, when a dry mud shell forms on the structural membrane of the Type-3 microphone, its sensitivity drops about 8 dB consistently below the first resonance at 3 kHz (the black curve in Fig. 8c). It appears that the dry mud shell becomes an additional layer of the structural membrane and contributes to the total stiffness of the membrane causing sensitivity drop below the resonance frequency.

To see if the microphone performance can recover after removing the mud residue, all microphone samples were wiped clean carefully with wet cloth and dried for another 24 hours before the final FR measurement. As shown by the grey dotted lines in Fig. 8, microphone Type-2 and Type-3 performance recover completely. After cleaning, the FR amplitude of microphone Type-1 is still slightly lower than the pretest curve, which may be owing to mud residue being trapped inside mesh pores thus effectively increasing the acoustic damping of the mesh layer.

5 Conclusions

As vehicle technology evolves, applications requiring externally mounted microphones or microphone arrays has gained attention in the automotive audio industry. In contrast to the indoor use environment, vehicle use conditions can be much harsher as vehicles could be driven in all kinds of weather and road conditions ranging for example from light to heavy rain, and from dry unpaved to wet muddy road. Foreign object contaminations and their influences on the acoustic behaviours of microphones pose a serious risk to the performance of applications relying on properly functioning microphones.

For automotive external microphones, the risk is not only concerned with the survivability (i.e., not being physically damaged), but also how stable the acoustic behaviours are under contamination conditions. Product IP ratings based on IEC 60529 standard or ISO 20653 standard may only be interpreted as an indication of the survivability after being exposed to certain level of water and dust contaminations. The IP ratings do not necessarily guarantee proper functionality during the time when the contamination condition presents. Furthermore, standard IP tests do not comprehensively cover all harsh operating conditions for vehicles such as driving on unpaved dirty road during heavy rain. Therefore, it is important to understand how automotive external microphone performance could vary under different contamination conditions and how well the performance can recover to the pre-contamination status after cleaning.

In this study, microphones of three design types were experimentally tested under four contamination conditions including water spray, water immersion, dry sand and dust, and wet mud. Their FRs were measured and compared before and after the contamination tests. It was shown that small amount of moisture or water exposure (e.g., water spray) did not cause appreciable performance change as long as the microphone porthole is reasonably protected by using at least a mesh layer. When large amount of wate, sand/dust or mud accumulated around the air pathway in front of the microphone porthole, both Type-1 and Type-2 microphone performance could change significantly due to the added mass and/or damping effects. For the Type-3 microphone that relies on a structural membrane to seal the microphone porthole thus removes the air pathway,

its FR was very robust against any forms of water and dry sand/dust contamination. On the other hand, FR changes of microphone Type-3 were seen under both wet and dry mud conditions. It is also interesting to notice that mud was the only condition that affected microphone Type-3 behaviour. Another important point worth mentioning is that, except for microphone Type-1 under the mud test condition, the pretest FR behaviour of all MUTs were basically recovered when the contamination condition was removed (i.e., cleaned and dried).

Three conclusions may be drawn from the above experimental observations: (1) foreign object contaminations such as water, dust and mud accumulation can lead to significant changes in microphone behaviours. (2) Microphone behaviour changes are mainly due to acoustic property shifting of the airpath between the external sound field and the sensing membrane. This means that classical microphone designs consisting of a porthole (e.g., Type-1 and Type-2) have relatively higher tendency to be affected by foreign contaminations then a sealed design (e.g., Type-3). (3) Changes due to foreign contamination may be temporary. Once detected and properly removed (e.g., cleaned), microphone performance of all design types may recover. However, more data are needed to further verify the last statement as the current study only tested one sample for each contamination condition. Statistically and empirically speaking, foreign contaminations could migrate into the microphone element through for example the porthole, causing non-recoverable damages.

In summary, this study provides direct experimental data related to automotive use scenarios and demonstrates how various contamination status could affect FRs of microphones with different weatherproofing design features. It is thus informative for engineers to choose proper microphone characteristics and design features to meet automotive external sound applications.

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