Estimation of Effectiveness of EMI Gaskets by using Results of Standardized Measurements

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***Abstract*—A technique for evaluating the effectiveness of the use of EMI gaskets is proposed. These conductive gaskets are designed to protect against electromagnetic interference and installed, for example, at the joints of metal sheets and in the slots of doorways of shielded rooms. The technique makes it possible to calculate the in-situ shielding effectiveness of an EMI gasket by using the standardized shielding effectiveness of this gasket (which is taken from the datasheet of the gasket or measured in accordance with applicable standards) and the geometrical characteristics of the places of gasket mounting (i.e., shape and size of the slot). The technique is validated by comparing the calculated and measured values of the shielding effectiveness in a wide frequency range (from 800 MHz to 18 GHz) for various types of the EMI gaskets (finger-spring gaskets, wire-mesh gaskets, conductive cloth pads) placed in slots of various sizes and shapes (straight, curved).**

Keywords—electromagnetic compatibility, electromagnetic shielding, EMI gaskets, electromagnetic measurements

I. Introduction

The shielding is one of the most commonly used methods for protecting a system (a vehicle, a ship, an aircraft, etc.) against the intended and unintended electromagnetic impact. There is a set of standards [1] – [9] used for measurement of the shielding effectiveness (SE).

IEEE Std. 299 [1] is intended for providing uniform measurement procedures and contains techniques for determining the effectiveness of electromagnetic shielding of enclosures having all dimensions greater than or equal to 2.0 m at frequencies from 9 kHz to 18 GHz (extendable to 50 Hz and 100 GHz, respectively). Standard IEC 61000-4-23 [2] contains test methods for verifying the protection levels provided by individual shielding components within the system and description of test procedures and measurements. Standard IEC 61000-4-21 [4] provides a technique for measurement of the SE of EMI gaskets by using a reverberation chamber. Standards ASTM D4935-18 [5] and SAE-ARP 1705-1981 [6] are based on the features of coaxial transmission line for measurement of the SE of samples made of conductive materials, absorbers, composites, or metamaterials in a wide frequency range.

Standard SAE-ARP 1173-2004 [7] provides a technique that can be used for testing of gaskets made of various materials (in accordance with [8]). Unfortunately, there are very little references about the use of this technique for measurement of gasket's SE in product catalogues published by manufacturers. On the contrary, standard MIL-DTL-83528 [9], which also determines the procedures of SE measurement for conductive gaskets, is widely used in the datasheets of manufacturers. Standard CHO-TP09 is similar to MIL-DTL-83528 [9], and it has wider scope; this standard is developed for a group of manufacturers of protection means, and only members of this group use it.

We suppose after [10] that MIL-DTL-83528 [9] is so popular by the following reason: for a given gasket, the values of the SE measured by [9] are much higher than the values measured by [7], so the manufacturers can promote their gaskets more effectively if they use [9] for the measurements.

The objective of this paper is to develop an analytical technique for calculating the in-situ SE of an EMI gasket installed in a slot of arbitrary size and shape by using the following initial data: geometric parameters of the slot and the gasket's SE measured according to the standard [7] or [9] (the latter SE can also be taken from the datasheet of the gasket). In addition, the technique must allow calculating the gasket's SE defined in terms of [7] (relative to slot) by using its SE defined in terms of [9] (relative to open window).

II. Estimation of Shielding Effectiveness of EMI Gaskets

A. Techniques for Measurement of Shielding Effectiveness

The procedure of measurement of screen's SE in accordance with [2] is in the measurement of the power P_0 received by the antenna installed inside an enclosure, when the window is open, and power P_P received when the window is closed by the protection solution under test (transmitting power and distance between antennas is constant during measurements). The corresponding SE for EM wave is calculated by formula:

$$S_P = 10\log(P_0/P_P). \qquad (1)$$

Definition of shielding effectiveness (1) corresponds to procedure of standard [9] for measurement of gasket SE. However, not only the gasket, but the metal sheet closes the window.

In accordance with [11], the shielding effectiveness of gasket (the contribution of gasket installed in slot in the wall

DOI: 10.1109/EMCEurope51680.2022.9901097

of enclosure) is defined as follows: at first, the initial shielding effectiveness of the enclosure with the open slot in window is obtained (S_S), at second, the SE of the enclosure (S_P) is obtained when the gasket is installed in the slot, and, finally, the difference between S_P and S_S (in dB) is calculated:

$$S_{is} = S_P - S_S . \qquad (2)$$

Definition (2) corresponds to measurements order described in standard [7] for SE of gaskets.

B. Proposed Technique

The proposed technique is based on the model of combined wall [15]. Technique allows obtaining the shielding effectiveness of materials from which protection solutions are made by using data of measurements made according to or similar to [9]. The value of the SE of combined wall (the wall consisting of regions with different SE) is evaluated by formula [11], [15]:

$$S_{c\,wall} = -10\lg\left(\sum_{i=1}^{N} 10^{-S_i/10} A_i / A_0\right), \qquad (3)$$

where A_i is the area of the region with SE of S_i and $A_0 = \sum A_i$ is the total area of a wall consisting of N regions.

SE S_g of gasket material can be calculated by formula that follows from (3):

$$S_g = -10\lg\left(\frac{10^{-0.1S_P} A_W - 10^{-0.1S_{\max}}(A_W - A_S)}{A_S}\right) \qquad (4)$$

where A_W is the area of open instrumental window; A_S is the area of the slot closed by gasket (calculated as slot width multiplied by total length of the slot); S_P is SE obtained in accordance with the technique of standard [9] and similar (see (1)); $S_{\max}$ is SE obtained for extremely reinforced window. For standard [9] assuming $S_{\max} = \infty$, obtain $S_g \approx S_P$ -20, where S_P is shielding effectiveness measured according to the standard.

In case of measurements according to the [7], $S_g \approx S_{is}$ given by measurements (when $S_{\max} >> S_{is}$, see Section III.C).

The proposed technique consists of two steps:

1) At first step, the SE S_g of gasket material is retrieved. First option is to directly use measurement results according to the standard [7] (or any similar technique measuring SE relative to the slot; the technique described in Section III can be used). The second option is to calculate S_g by (4) using data measured according to the standard [9] (or any similar technique measuring SE relative to open window).

2) At second step, in-situ SE $S_{c\,wall}$ is calculated by substituting the following in (3): area of slot protected by the gasket, retrieved value of S_g, and parameters of other regions.

III. Validation of Proposed Technique

A. Test Site for Measurements of Shielding Effectiveness by using Multipurpose Measuring Cabin

The laboratory has its own test site with multipurpose measuring cabin (the Cabin). The Cabin has instrumental window of specified dimension. The Cabin is well shielded to decrease the penetration of the EM radiation inside its volume through all elements except the instrumental window. Based on this Cabin, the measuring setup, which corresponds to the procedures described in standards [1] – [3], [7], [9] and allows definition of the gasket SE, is developed (Fig. 1).

The transmitting test antenna is installed outside the Cabin. The radiation axis of this antenna coincides with the normal to the center of the instrumental window. The receiving test antenna of the same type as transmitting one is mounted inside the Cabin in close proximity to instrumental window. Working polarizations of antennas must coincide.

There are some general problems dealing with the measurements of the protection solutions SE [2]: the measurements of shielding effectiveness of meshes, conductive covers, and honeycombs installed in aperture must take into account that the EM wave propagating through the open aperture is not a plane wave for low frequencies. But for frequencies, which are more than the cut-off frequency of waveguide associated with aperture, the wave can be considered as plane wave.

The following requirements must be satisfied for measurement of SE for plane EM-wave.

The dimensions of the aperture (instrumental window) and the minimum frequency of testing are related with each other by the inequality [2]:

$$f_{\min} > f_{cr} = c/(2\cdot\max(a,b)), \qquad (5)$$

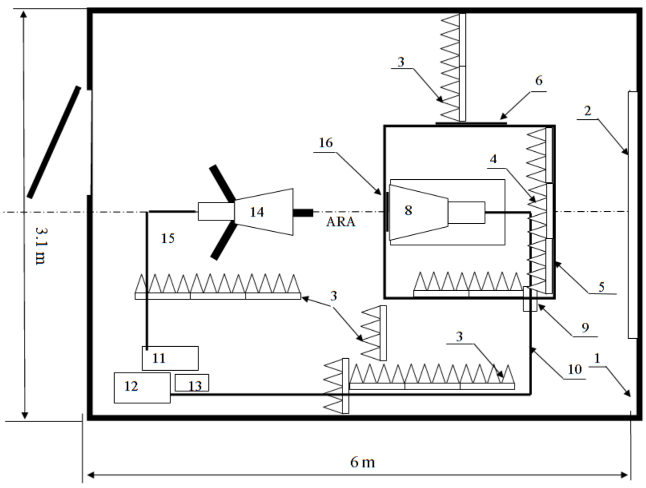

Fig. 1. Diagram of test site and measuring setup: 1 – wall of room; 2 – window of room; 3 – RAM panels (Tora-39) inside the room; 4 – RAM panels (Tora-39 and Tora-9) inside the Cabin; 5 – walls of the Cabin; 6 – door of the Cabin; 7 – dielectric support for receiving antenna; 8 – receiving antenna; 9 – antenna input (feedthrough connector) of the Cabin; 10 – coaxial cable connecting receiving antenna with spectrum analyzer; 11 – RF generator; 12 – spectrum analyzer; 13 – control PC; 14 – transmitting antenna; 15 – coaxial cable connecting RF generator and transmitting antenna; 16 – instrumental window of the Cabin.

where a,b are dimensions of aperture, f_{cr} is the cut-off frequency of waveguide associated with aperture. The maximum dimension of instrumental window is 30 cm and measuring horn antennas with dimension 30×20 cm of aperture are used in the frequency range starting at 800 MHz.

Transmitting antenna must be installed in far-field zone from the sample under test. A condition of far-field zone boundary r_{far} for the frequency f is [12]:

$$d_0 \geq r_{far} = \lambda / 2\pi \,, \qquad (6)$$

where d_0 is distance between the transmitting antenna and instrument window, $\lambda = c/f$ is wavelength; c is speed of light in free space.

The distance dr between the instrumental window of the Cabin and aperture of receiving antennas must be as small as possible [2] for the measurements of SE of protection means (screens, gaskets, etc.):

$$dr << \min(a,b) \,. \qquad (7)$$

The normal incidence of radiation on the instrumental window is required: $\psi = 0°$ [2].

Results of measurement of the shielding effectiveness of gasket depend on the parameters of a slot protected by the gasket. This fact is noted in [13], [14].

B. Technique for Measurement of Shielding Effectiveness

The measurement of the shielding effectiveness of gaskets in the framework of the developed technique is performed by the following procedure using the Cabin.

At start, the calibration is performed. The received power P_0 is measured when the generator produces the predefined power, and instrumental window of the cabin is open.

Before the measurements of shielding effectiveness of protection solution, the minimum value of received power $P_{\min}$ that correspond to extremely reinforced instrumental window is obtained. For reinforcing, the instrumental window of the Cabin is closed by the metal cover; the conductive gaskets of maximum shielding effectiveness are used for reinforcing slots between the metal cover and frame of the window; the region of the slot is additionally reinforced by 2..3 layers of metal foil. Maximum measurable SE is $S_{\max} = -10\log(P_{\min} / P_0)$.

Then the window is closed by the metal cover, and the slot between the cover and the frame is filled by the dielectric having the same thickness (and shape) as the EMI gasket under test. The power P_S penetrating through the slot filled by dielectric is measured. The obtained value P_S (for each frequency) is substituted in (1) instead of P_P, and the SE S_S of the open slot is calculated.

$$S_S = 10\log(P_0 / P_S) \,. \qquad (8)$$

After that, the slot is filled by the EMI gasket under test, and the power P_P is measured. This procedure determines the value of S_P by (1).

Finally, the shielding effectiveness of the EMI gasket under test is defined in dependence on the used standard. For the technique described in [9], the resulting SE is (1). For standard SAE-ARP 1173 [7], SE is defined by (2).

Difference between S_P and S_S in (2) is determined only by the contribution of the gasket because the contribution of other paths of EM energy penetration inside the Cabin is fixed in the given conditions of experiment. In other words, definition of the shielding effectiveness for measurements (2) takes into account material of gasket, its structure, and peculiarities of mounting the gasket in the slot.

The power received by the antenna mounted in the Cabin is determined by the energy penetrating into the Cabin through various regions of enclosure (slot, metal sheet, etc.) and accumulated in its volume. The power of EM radiation penetrating through the slot filled by dielectric is denoted as P_{dg}; P_{ot} is the power of EM radiation penetrating through the other regions of the Cabin walls. The power of reverberation component (corresponding to the EM power accumulated inside the volume of the Cabin) is denoted as P_{acc1}. So, the power of EM radiation inside the Cabin is as follows:

$$P_1 = P_{dg} + P_{ot} + P_{acc1} \,. \qquad (9)$$

The presence of term P_{acc1} in (9) can sufficiently change the experimental results for shielding effectiveness of gasket due to resonances inside the Cabin. When the Q-factor of the Cabin is large, the amplitude of field in resonances is large, too. For elimination of this effect, RAM (radiation absorbing material) panels, which decrease the amplitude of the reverberation component, are mounted inside the Cabin.

When the conductive EMI gasket is present in the slot, then the value of the power inside the Cabin is as follows:

$$P_2 = P_{cg} + P_{ot} + P_{acc2} \,, \qquad (10)$$

where P_{cg} is the power provided by the penetration of EM radiation through the slot closed by EMI gasket under test; P_{acc2} is the power of reverberation component. The value of P_{ot} does not depend on the state of the slot under consideration.

The error of SE measurement by the developed setup is determined by the values P_{acc1} and P_{acc2}, which should be minimized by the increasing of insertion losses provided by RAM. Further elimination of the contribution of reverberation component is connected with the choice of dimension of the instrumental window and parameters of receiving antenna (dimension, location, construction, antenna pattern). If the high-directional horn antenna with aperture of dimensions no less than the dimensions of instrumental window is used for measurements as a receiving antenna and it is mounted in close proximity to the instrumental window, then the impact of reverberation component on result of measurements will be eliminated (see Fig. 1). Due to removing the reverberation component of field and receiving almost all electromagnetic energy penetrating into the Cabin by the horn antenna, the developed measuring setup does not require detection of worst-case location of the receiving antenna as opposed to the single-point measurements.

Based on the model of the combined wall (3), one can write the following formulas for the shielding effectiveness of the Cabin window in the cases of absence and presence of the EMI gasket, respectively:

$$S_{1P} = -10\lg\left(\frac{p_{dg}A_1 + p_{ot}(A_0 - A_1) + P_{acc1}}{p_0 A_0}\right),$$
$$S_{2P} = -10\lg\left(\frac{p_{cg}A_1 + p_{ot}(A_0 - A_1) + P_{acc2}}{p_0 A_0}\right), \tag{11}$$

where A_1 is the area of the considered slot, A_0 is the full area of the illuminated wall of the Cabin (the area of instrumental window when aperture of horn antenna coincides with the window), p_0 is the power flux density of the incident radiation, p_{dg} is the power flux density of radiation penetrating inside the enclosure through the slot filled by the dielectric gasket, p_{cg} is the power flux density penetrating through the slot filled by the EMI gasket under test, p_{ot} corresponds to the penetration of EM energy through other parts of the wall (window), P_{acc1} and P_{acc2} are the powers corresponding to the reverberation component.

In the case of absorbers presence, the power corresponding to the reverberation component can be neglected:

$$S_{is} = -10\lg\left(\frac{p_{cg}A_1 + p_{ot}(A_0 - A_1)}{p_{dig}A_1 + p_{ot}(A_0 - A_1)}\right), \tag{12}$$

So, the shielding effectiveness obtained by testing in accordance with definition (2) can be expressed from the measured values as follows:

$$S_{is} = 10\lg(P_1 / P_2), \tag{13}$$

where $P_1 = P_{dg} + P_{ot}$ is the power at the output of receiving antenna when the slot is filled by dielectric; $P_2 = P_{cg} + P_{ot}$ is the power at the output of receiving antenna when the slot is filled by EMI gasket under test.

For the constant power at the input of transmitting antenna $P_{in} = const$, one can write:

$$\frac{P_1}{P_2} = \frac{P_1}{P_{in}} \cdot \frac{P_{in}}{P_2} = \frac{F_1}{F_2},\ F_1 = \frac{P_1}{P_{in}},\ F_2 = \frac{P_2}{P_{in}}, \tag{14}$$

where F_1, F_2 are the antenna-to-antenna coupling factors (AACF) for cases when the receiving antenna is placed behind the instrumental window with open slots, and when slots are reinforced by EMI gasket under test, respectively. Note that (14) is true for any P_{in}. The distance between antennas is the same in both cases. Finally, AFC of measured SE is expressed in dB by formula:

$$S_{is}(f) = 10\log(F_1(f)) - 10\log(F_2(f)). \tag{15}$$

C. Estimation of Measurement Error of Developed Setup

The value S_g of SE for the region corresponding to the gasket can be expressed from $S_{c\,wall}$ (3) only if SE values of other regions ($i \neq g$) are known. The same conclusion follows from (12): it is necessary to obtain the power $P_{ot} = p_{ot}(A_0 - A_1)$ penetrating through the other regions of the illuminated instrumental window.

Suppose that the power penetrating through the regions excluding the slot in instrumental window P_{ot} is equal to $P_{\min}$, where $P_{\min}$ is the measured value of the received power for the extremely reinforced window. Having the value of P_{ot}, it is possible to make a correspondence between the shielding effectiveness obtained by measurements and value of SE of gasket material S_g calculated by analytical model or specified by manufacturer.

According to (12) and (13), the shielding effectiveness of gasket's material can be estimated as:

$$S_g = 10\lg\left(\frac{P_{dg}}{P_{cg}}\right) = 10\lg\left(\frac{P_1 - P_{ot}}{P_2 - P_{ot}}\right) \tag{16}$$

As it follows from (13) and (16), the obtained values of S_{is} and S_g must coincide when $P_{ot} = 0$. It means that the reinforcing all parts of the Cabin leads to the desirable result.

The upper limit of gasket SE, which can be measured by the technique, is defined by inequality: $P_2 \le P_{ot}$, when calculations based on (16) are impossible.

The developed measuring setup for SE measurements in the high-frequency range (see (5)) is based on the use of the high-directional horn antennas; therefore, the setup provides the sufficient accuracy when dimensions of instrumental window are less or equal to the dimensions of aperture of the receiving horn antenna and this antenna is located in close proximity of instrumental window. Other parts of the Cabin are shielded as well as possible. In these conditions, parameters $p_{ot}(A_0 - A_1)$ in (12) tend to zero, and gasket SE S_g obtained by measurement will be as accurate as possible. Physically, the developed measuring setup is similar to the setup of coaxial test procedure [5], [6]; the developed setup allows taking into account not only the shielding properties of material, but features of the slot under protection, too.

D. Analysis of Measurement Results

First, the antenna-to-antenna coupling factors (AACFs) are measured without the EMI gaskets in the following situations: 1) the instrumental window (30×20 cm) is open; 2) the instrumental window is closed by a metal cover, and only the 1-mm slot on the window perimeter is open; 3) the square aperture (10×10 cm) is open in the instrumental window; 4) the slot of 1 mm width is present on the perimeter of the square aperture closed by a metal cover; 5) the circular aperture of 10 cm in diameter is open in the instrumental window; 6) the slot of 1 mm width is present on the perimeter of the circular aperture closed by a metal cover; 7) the instrumental window is extremely reinforced. Measurement results are shown in Fig. 2. The lines shown in figures below (except the dotted red line in Fig. 2) are obtained by smoothing the raw data with help of a piecewise symmetric k-nearest neighbor linear least square fitting procedure in which k is chosen adaptively.

Note: the uniformity of gasket mounting conditions must be provided in all of cases; in particular, dielectric screws are

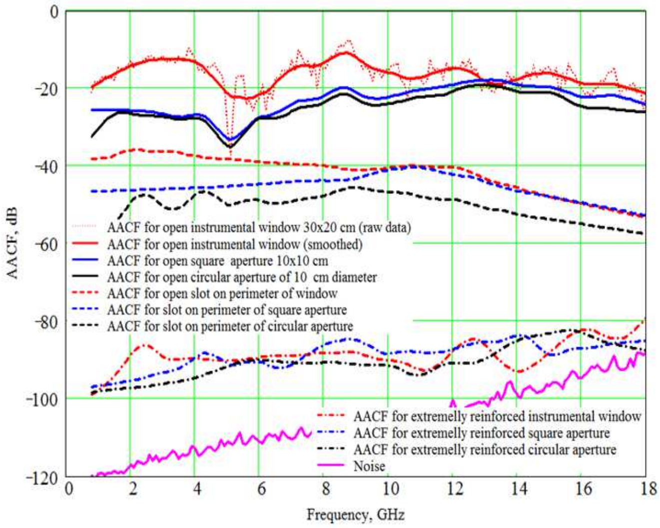

Fig. 2. Antenna-to-antenna coupling factors (AACFs) measured in different situations without gaskets.

used for mounting metal cover on window and apertures to provide the uniformity of the slot.

Then, the EMI gaskets are inserted in the slots described above, and the corresponding AACFs are measured. Based on the measured AACFs, S_P (1) and S_{is} (15) are obtained.

Solid lines (calculated results) in Figs. 3-6 show the results of calculation by (4) in which the geometric parameters of slots and windows, the values of S_P measured in accordance with [9], and the measured value of $S_{\max}$ are substituted. The value of $S_{\max}$ is obtained as the differences between the AACFs measured for the open instrumental window (or square/circular aperture) and for the extremely reinforced window (see Fig. 2).

The following types of gaskets are analyzed: wire mesh gasket ES6X4-6AC4-5M (Fig. 3); conductive cloth pad 3020503 WE-LT (Fig. 4); finger spring gasket JOVI 1605-01 (Fig. 5); finger spring gasket JOVI-1250-0S/N (Fig. 6).

The comparison of dotted and solid lines in Figs 3 – 6 shows that the gaskets' SE in terms of [7] (relative to slot) can be estimated by (4) on the basis of SE measured in accordance with [9] (relative to open window). The difference between the gasket's SE defined in terms of [9] and in terms of [7] is about 20 dB.

For gasket ES6X4-6AC4-5M, the manufacturer's data is known [16]. Presumably, the manufacturer used an analogue of the standard [9]. The measurement results are consistent with the manufacturer's data (see red line with crosses and turquoise points in Fig. 3).

For gasket 3020503 WE-LT, there are also manufacturer's measurements [17], but it is unknown by which measurement setup they were obtained (see Fig. 4).

Finally, the possibility of calculating the in-situ SE of an EMI gasket installed in a slot of arbitrary size and shape by using the developed technique is confirmed as follows. The shielding effectiveness of the gasket material is calculated by (4) in which the measured SE of the gasket JOVI-1250-0S/N installed in the slot of full instrumental window is substituted. The obtained value S_g is substituted in (3) for the calculation of the SE in situations when the same gasket is

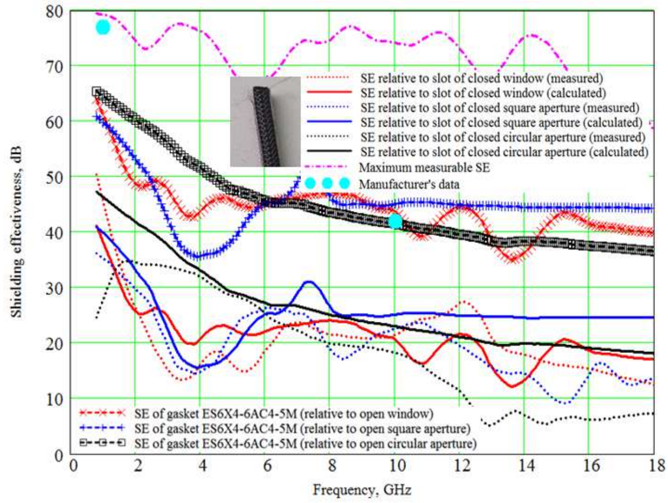

Fig. 3. Shielding effectiveness of wire mesh gasket ES6X4-6AC4-5M.

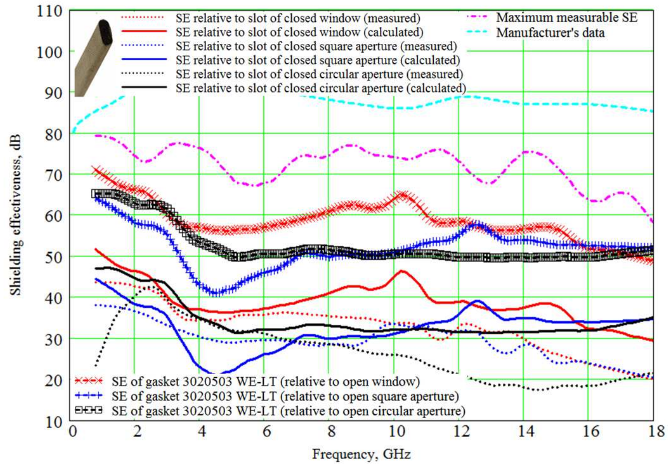

Fig. 4. Shielding effectiveness of conductive cloth pad 3020503 WE-LT.

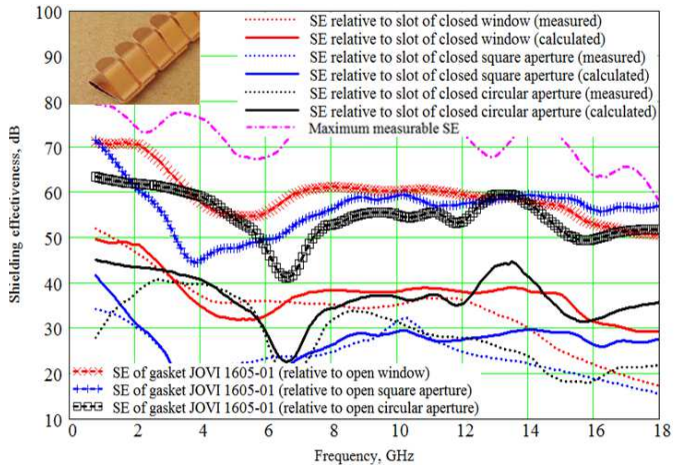

Fig. 5. Shielding effectiveness of finger spring gasket JOVI 1605-01.

installed in the slot of square aperture and in the slot of circular aperture (N=2, $S_1 = S_g$, $S_2 = S_{\max}$ for calculation by (3)). Value of $S_{\max}$ in (3) corresponds to SE of the instrumental window (or square/circular aperture) closed by the metal cover in dependence on the type of situation under analysis. Then the obtained results are compared with the results of measurements of SE for corresponding apertures.

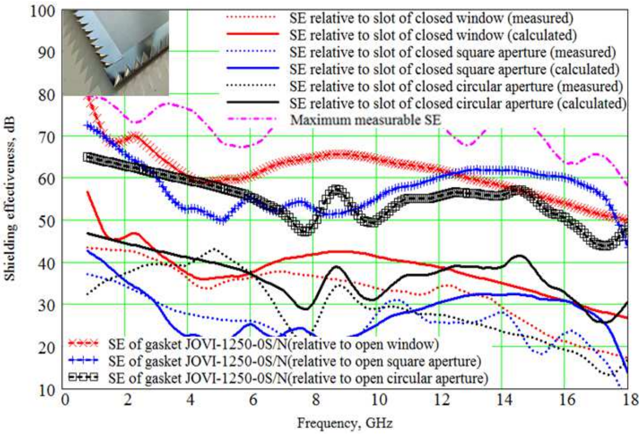

Fig. 6. Shielding effectiveness of finger spring gasket JOVI-1250-0S/N.

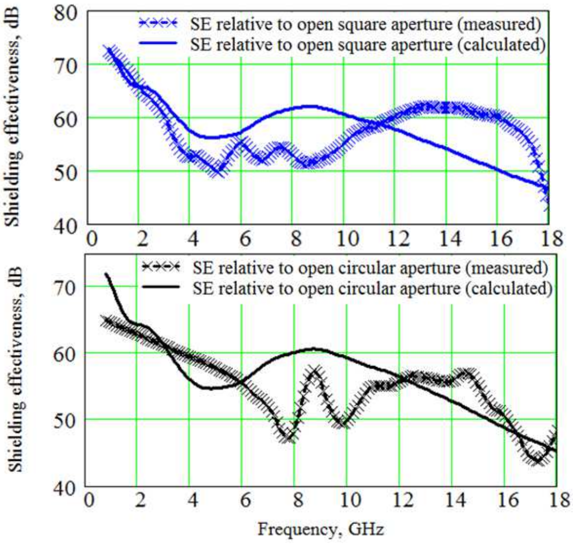

Fig. 7. Shielding effectiveness of finger spring gasket JOVI-1250-0S/N.

The comparison (Fig. 7) confirms the ability of using the proposed technique for estimation of the gasket's contribution to SE of combined walls with slots having various sizes and shapes and protected by gaskets.

As regards the slot parameters, the following peculiarities of SE measurements are established empirically. For taking into account the polarization of incident radiation and orientation of the slot, the effective length of the slot used for calculation of its area is obtained by multiplying of the geometrical length by sine of the angle between E-vector of incident EM wave and the direction of the slot.

The developed setup for SE measurement is suitable for frequencies that are larger than the cut-off frequency determined by geometrical length of the slot. As it is shown in [11], for the low frequencies ($f_{\min} < f_{cr}$ in (5)), the aperture (slot) has non-zero intrinsic SE, and results of measurements are the difference of the SE of combined wall (with slot having intrinsic SE) and SE of the same wall when the slot is reinforced by the EMI gasket under test.

IV. Conclusion

The proposed analytical technique makes it possible to estimate the in-situ shielding effectiveness (SE) of a gasket by using the standardized SE of this gasket (the standardized SE can be taken from the datasheet or measured). Therefore, the technique can be used for assessing the contribution of EMI gaskets into the SE of equipment cases, vehicle bodies, ship hulls, etc. [11]. The fast estimation of the SE provided by analytical calculations is important, since a tight schedule for the development of new products hardly ever allows organizing measurements of the in-situ SE.

The proposed technique is also useful for comparing the gasket's SE measured by different setups.

The developed measuring setup makes it possible to reduce the cost of measurements of gaskets' SE as compared to the standard methodology, because shielded or reverberation rooms are replaced by a compact and relatively cheap shielded cabin.

The validation results prove the operability of the proposed calculation technique and developed measuring setup at frequencies of 0.8–18 GHz.

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