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Surface microphones: a calibration method proposal based on IEC 61094-5

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Abstract

Surface microphones are especially used on aeronautical and automotive applications. One of the main struggles concerning reliability in its usage is to ensure the maintenance of specifications through periodic calibrations. Models that are designed with a metal membrane, in principle, could be calibrated by a special type of electrostatic actuator, provided that the laboratory possess the accessories required for such a fixation and testing. However, the design and type of encapsulation that is most common does not always enable this calibration modality. In general, surface microphones are calibrated solely during the manufacturing process, so much so that just a mere sensitivity check is left to assure stability, on one or two frequencies, naturally, considering that appropriate adapters for coupling are available to the user. Still, this sensitivity check is also challenging because the physical structure of this type of microphone is such that does not allow it to be inserted directly into the coupler of a sound level calibrator. Admittedly, any adapter provided by the manufacturer will necessarily go along with problems such as volume, leakage, and acoustic insulation. In this context, the periodic calibration of surface microphones, performed by accredited laboratories, would represent a huge metrological advance, and would support confidence in the results of measurements based on these transducers, such as with any other measurement microphone. This work aims to evidence the feasibility of determining sensitivity and frequency response using one of the mounting configurations described by IEC 61094 5. In this configuration the standard microphone and the surface microphone are arranged face-to-face, orthogonally to the sound field. The source is excited with a sine-sweep and the reference value is given by a standard laboratory microphone, calibrated by reciprocity in pressure field. Furthermore, the work envisions the possibility of a free-field test configuration based on IEC 61094-8.

Keywords: Surface Microphone, NVH, Periodic Calibration, Comparison jig

Resumen
Micrófonos de superficie se usan especialmente en aplicaciones aeronáuticas y automotivas. Una de las principales dificultades para la confiabilidad en su utilización es garantizar el mantenimiento de las especificaciones a través de calibraciones periódicas. Los modelos diseñados con membrana metálica, en general, pueden ser calibrador por un tipo especial de actuador electrostático, siempre que el laboratorio disponga de los accesorios necesarios para testar dicho transductor. Sin embargo, el tipo de encapsulamiento más común no brinda la posibilidad de esa modalidad de calibración. En general, esos micrófonos se calibran solamente en su proceso de fabricación, quedando la simple verificación de la sensibilidad, en una o dos frecuencias, asumiendo que el usuario disponga de los adaptadores adecuados para el acoplamiento. Aun así, esa verificación de sensibilidad sigue siendo un reto, porque la estructura física de ese tipo de micrófono no permite introducirlo directamente en un calibrador de nivel sonoro. Cualquier adaptador que el fabricante provea necesariamente convive con problemas como volumen, fuga y aislamiento acústico del compuesto. En ese contexto, la calibración periódica de micrófonos de superficie, hecha por laboratorio acreditados, representaría un enorme avanzo metrológico y cimentaría la confianza en los resultados de las mediciones con dichos transductores, siguiendo la misma praxis de cualquier otro micrófono de medición. El presente trabajo anhela evidenciar la viabilidad de la determinación de sensibilidad y respuesta en frecuencia usando una de las configuraciones de ensamble descritas por la IEC 61094-5. En dicha configuración, el micrófono de referencia y el micrófono de superficie se ponen faz-a-faz, ortogonalmente a la fuente sonora. La fuente se excita con un barrido sinusoidal y el valor de referencia se da por un micrófono patrón laboratorial calibrado por reciprocidad en presión. Además, el trabajo figura la posibilidad de una configuración de prueba en campo libre basada en la IEC 61094-8.

Palabras-llave: Micrófono de superficie, NVH, calibración periódica, *Comparison jig*

Resumo
Microfones de superfície são usados especialmente para aplicações aeronáuticas e automotivas. Uma das principais dificuldades para a confiabilidade na sua utilização é assegurar a manutenção das especificações através de calibrações periódicas. Modelos projetados com membrana metálica, em princípio, podem ser calibrados por um tipo especial de atuador eletrostático, desde que o laboratório disponibilize dos acessórios requeridos para sua fixação e teste. Porém, o projeto e o tipo de encapsulamento mais comuns nem sempre possibilitam essa modalidade de calibração. Em geral, microfones de superfície são calibrados apenas durante o processo de fabricação, restando executar a mera verificação de sensibilidade, em uma ou duas frequências, considerando que adaptadores apropriados para o acoplamento estejam disponíveis ao usuário. Ainda assim, esta verificação de sensibilidade representa um desafio porque a estrutura física deste tipo de microfone é tal que não lhe permite ser introduzido diretamente na cavidade de um calibrador de nível sonoro. Qualquer adaptador provido pelo fabricante necessariamente irá conviver com problemas, tais como, volume frontal, vazamento e isolação acústica do conjunto. Neste contexto, a calibração periódica de microfones de superfície, executada por laboratórios acreditados, representaria um enorme avanço metrológico e alicerçaria a confiança nos resultados das medições com estes transdutores, seguindo a mesma prática de qualquer outro microfone de medição. Este trabalho pretende evidenciar a viabilidade de se determinar a sensibilidade e a resposta em frequência utilizando uma das configurações de montagem descritas pela IEC 61094-5. Nessa configuração o microfone padrão e o microfone de superfície são dispostos face-a-face, ortogonalmente à fonte sonora. A fonte é excitada com uma varredura de senos e o valor de referência é dado por um microfone padrão laboratorial calibrado por reciprocidade em pressão. Ademais, o trabalho vislumbra a possibilidade de uma configuração de teste em campo livre baseada na IEC 61094-8.

Palavras-chave: Microfone de superfície, NVH, calibração periódica, *Comparison jig*

1. INTRODUCTION

Microphone calibration is paramount when precision in sound pressure measurements is attempted. Even though the sensitivity obtained by means of a sinusoidal excitation in 1 kHz is commonly used as an indicator of proper functioning for a microphone, this parameter is not enough to assure the stability of the response on the whole frequency range. This is seen is cases like a very small perforation on the membrane that could produce a sharp loss of sensitivity for lower frequencies, or, on the other hand, some stress or wrinkle in the membrane could significantly alter the high frequency response shape. Calibration is the only resource that allows control of the microphone's performance at the sound field for which it was designed, whereas the response at other sound fields could substantially diverge. For instance, at 10 kHz a difference of approximately 5 to 8 dB between pressure field and free field is inherently expected.

The microphones targeted in this study, namely surface microphones, are designed for pressure field. The calibration methods for microphones designed for this sound field are specified at IEC 61094-2 (reciprocity), IEC 61094-5 (comparison at pressure field) and IEC 61094-6 (electrostatic actuator). However, the reciprocity method cannot be applied to surface microphones, but only to laboratory standard microphones, such as the Brüel & Kjær 4180 used as a reference in this study.

The electrostatic actuator method applies to microphones that have removable grids and metallic membranes, resulting in a fair approximation of the pressure field response. Nonetheless, not but a few of surface microphone models have such an exposed membrane that could make the actuator method feasible for calibrating those.

Evidently, a laboratory that intends to offer this type of calibration needs the accessories, both an actuator that correctly attaches to the surface microphone's capsule, but also for coupling the microphone to a pistonphone or sound level calibrator (Image 1). This is due to the need for a more stable and reliable means to obtain the absolute sensitivity, usually in [mV/Pa], once the own standard does not recommend using a sensitivity estimated directly using the electrostatic actuator.

Image 1: Left: Surface Microphone Actuator; Right: Accessory for coupling the microphone's capsule to a sound level calibrator. Images from GRAS website.

The inherent constructive characteristics of the microphone's capsule do not allow its insertion in the coupler of any given sound level calibrator. Hence, complexities related to the additional volume and length from the top of the adaptor to the sound source on the other end of the calibrator's coupler, as well as the possibility of pressure leakage are a threat in this modality of sensitivity determination by means of adaptors and accessories.

The part 5 of IEC 61094 series presents a method for comparison in pressure field and develops in several techniques. The technique of comparison in a coupler can be proceeded simultaneously or sequentially. On the former, microphones are inserted in each side of the comparison coupler and have their membranes disposed face-to-face, while a transducer is excited providing a sound pressure in this small space in between the membranes. On the sequential technique, the coupler has a built-in fixed reference microphone that functions as a multifrequency sound level calibrator. For both cases, the microphone under test must be introduced inside the coupler to minimize volume and distance between it and the reference microphone. For that reason, it is not possible to apply such techniques to surface microphones.

Nevertheless, there is still another technique in this part of the standard, identified as "comparison jig" that consists in a mounting configuration that has both test and reference microphones disposed face-to-face in stems, which in turn are positioned orthogonally to the sound source. This last technique is viable to surface microphones. Clearly, some adaptations for this procedure are required, such as the impossibility of crossing measuring chains of reference and test channels once surface microphones have built in circuits for IEPE signal processing. This leads to an increasing on uncertainty estimation, by virtue of keeping errors and uncertainties related to the measuring chains, that would typically be mathematically eliminated in this technique. Even so, this opens the possibility of a thorough verification of the surface microphone, both in its frequency response in the whole range, and in its absolute sensitivity likewise, as this information is a natural outcome of this comparison technique to a laboratory standard microphone. Moreover, this sensitivity derived from this technique is probably more precise than the one obtained by means of a sound level calibrator with attaching accessories, once both microphones are simultaneously excited, and the reference channel sensitivity is well known.

The present work is a mere introduction to that possibility, opening the way to testing other surface microphone brands and models, besides contributions to measuring uncertainty estimation. An alternative possibility to consider in the future would be the test by IEC 61094-8. Despite being a free-field calibration standard, it could be considered that the results for microphones when disposed at 90º in relation to the sound source lead eventually to a pressure-field condition.

2. IEC 61094-5 COMPARISON JIG TECHNIQUE APPLIED TO SURFACE MICROPHONES

The comparison jig technique described in IEC 61094-5 (Image 2) consists in submitting both microphones, namely, the reference and the test microphones, simultaneously to the same sound pressure. Those microphones are disposed facing each other in such a way that their membranes remain face-to-face less than 1 mm apart. The associated measuring uncertainty is considerably reduced, once the technique requires swapping of reference and test microphones to opposite measuring chain, before proceeding another frequency response measurement. This results in mathematically canceling the measuring chains errors, this is remarkable specially at lower frequencies that are heavily influenced by capacitance coupling effects. However, this channel swapping only works with traditional capacitive microphones, whether externally polarized or pre-polarized. The sound wave produced by the sound source is propagated orthogonally to the theoretical line that pass through the pre-amplifiers and microphones, so much so that they are excited by the very same sound pressure.

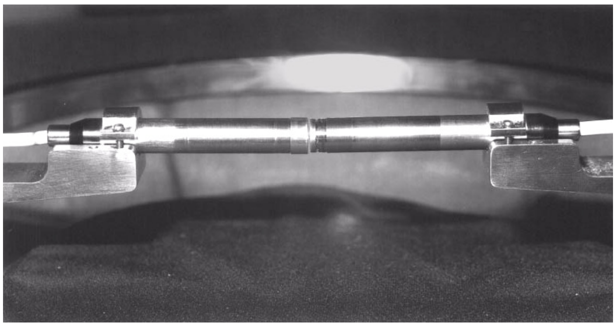

Image 2: Comparison jig for calibration in pressure-field. Image from IEC 61094-5.

Adapting this technique to surface microphones demands some sacrifices. The first and foremost is that the channel swapping is not possible. Yet, since a great deal of surface microphones currently cannot be calibrated in the whole frequency range, giving up the best capacity for the aforementioned IEC 61094-5 technique is worth it. Furthermore, the reference microphone could be calibrated attached to the rest of the measuring chain to determine the sensitivity of the whole set (microphone, pre-amplifier and measuring system), using this final information as reference for sound pressure in the test. The reference channel sensitivity could also be adjusted by means of a reference sound level calibrator, ignoring the open circuit sensitivity of the microphone capsule, as it will be always attached to the same measuring chain. A secondary issue would be related to this method requirement for higher frequencies, that is, the maximum frequency allowed is inversely proportional to the distance between the test and reference microphones membranes. This could raise some concerns, once surface microphones that cannot be calibrated by means of electrostatic actuator do not allow its protective grid to be removed. Yet, it the relevant frequency range of surface microphones is not usually higher than 10 kHz. Thus, even mounting a microphone with the grid attached in this comparison jig would comply to the necessary distance between membranes for this frequency range.

In the present work, the surface microphones were affixed with a double-sided tape on the tip of a ½" microphone (damaged), just as a support for positioning. Image 3 shows the final result of the comparison jig mounting. Fixing surface microphone on the damaged microphone capsule also makes easier its alignment and positioning in relation to the sound source as well as the distance to the reference microphone.

Image 3: Face-to-face microphone mounting, orthogonally to the sound wave direction, based on the configuration specified in IEC 61094-5.

Image 3 shows at the right side the reference microphone Brüel & Kjær 4180, calibrated by reciprocity in pressure-field, attached to a Brüel & Kjær 2669 pre-amplifier. On the left side the surface microphone fixed to a damaged microphone and attached to a ½" pre-amplifier. Both the damaged microphone and the pre-amplifier are not important besides its utility in allowing to place the surface microphone in this face-to-face configuration in relation to the reference microphone, as indicated by IEC 61094-5.

Regarding the excitation signal, the sound source could be excited by sinusoidal pure tone signals in third octave steps. Nevertheless, for this study, the sound source was excited by a sine-sweep and the resulting electric signals were processed by a system with capacity to manage Time Selection Technique (TST). Naturally, in contrast with the processing needed for a free-field simulation, it is not necessary to apply a narrow window, as the microphones are positioned very close to the sound source. Conversely, a broad windowing is applied aiming to diminish background noise and distortion, so much so that a simple smoothing could be enough to an appropriate comparison. Image 4 shows the result of this process.

Image 4: Frequency response of reference and surface microphones in a face-to-face configuration, excited by a sine-sweep and processed by TST.

The laboratory standard microphone Brüel & Kjær 4180 is calibrated by reciprocity in pressure-field by Inmetro (Brazilian primary laboratory), providing the best-case scenario relative to its uncertainty. This microphone also has calibration by reciprocity in free-field, allowing it to be used as reference also in tests with frontal incidence of the sound wave. The measuring system used was a CMF 42, with the reference channel configured for a LEMO connector with an external 200 V polarization, whereas the surface microphone channel was configured to an IEPE supply in a BNC connector acquisition.

3. TEST AND RESULTS

In order to confirm the theory that the pressure-field technique in discussion could be adapted to surface microphones, four samples of a same model microphone, namely GRAS 40PS (Image 4), were tested and compared to the manufacturer's initial calibration. This microphone does not allow its protection grid to be removed, reflecting the exact limitation this technique could solve.

Image 5: GRAS 40 PS with silicon rubber fairing. Image from GRAS website.

3.1 Manufacturer Calibration

Each microphone has an individual calibration chart provided by the manufacturer (Image 6). Yet, the chart does not specify how the calibration is proceeded. It just mentions a pistonphone and a ¼" pressure-field microphone as references for this initial calibration. One could only speculate that these results are obtained by some kind of sequential comparison between each surface microphone and the reference mentioned, and the absolute sensitivity in 250 Hz is achieved using the pistonphone and adaptors to attach the microphone to its orifice, once it could not be inserted in the microphone coupler for mechanical limitations.

Another limitation of this initial calibration is that it does not indicate the associated measuring uncertainties for any value or frequency range. Moreover, the only numerical value concerning the microphone that is provided is the absolute sensitivity. Even this value does not make explicit to which frequency it refers, although it could be deduced by the indicated reference pistonphone. All the other sensitivity values are just plotted in a graphic. It is good to mention that those charts are from 2011, and maybe the layout of this calibration chart provided by the manufacturer could be currently different.

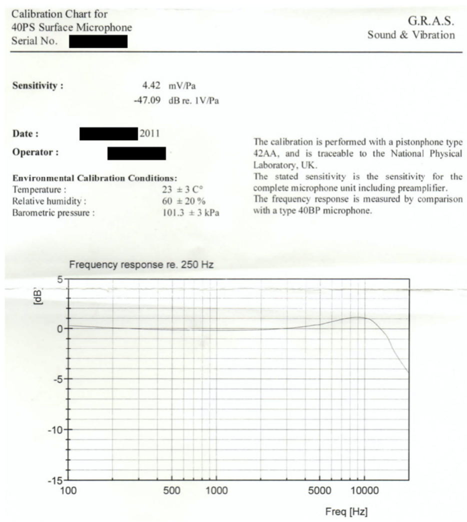

Image 6: GRAS 40 PS initial calibration chart.

Nonetheless, to the effects of this work some assumptions are made. First, that the values reported by the manufacturer are reliable, considering the limitations of the methods used, and that they reflect the state of the microphone when it left their facilities. Second, once this information is not available, that the uncertainties associated to the values reported by the manufacturer has roughly the same magnitude of the uncertainties estimated by the proposed IEC 61094-5 technique. Finally, as the charts were printed, they charts were scanned and an Adobe Acrobat tool for measuring images in a document was used to estimate the exact numerical deviation value associated to each frequency. The result of this was a third-octave frequency response table, normalized at 250 Hz and with two digits precision, used as the reference values, as showed in Table 1. The data considered is only up to 12,5 kHz, that is the specified frequency range for this microphone model. The serial numbers of each microphone were codified.

Freq [Hz]	SM-1 [dB]	SM-2 [dB]	SM-3 [dB]	SM-4 [dB]
100	0,37	0,29	0,28	0,33
125	0,21	0,23	0,22	0,25
160	0,17	0,16	0,13	0,18
200	0,08	0,07	0,06	0,08
250	0,00	0,00	0,00	0,00
315	-0,10	-0,07	-0,07	-0,09
400	-0,14	-0,11	-0,12	-0,16
500	-0,20	-0,14	-0,15	-0,20
630	-0,24	-0,19	-0,16	-0,24
800	-0,32	-0,21	-0,17	-0,29
1000	-0,35	-0,23	-0,18	-0,35
1250	-0,41	-0,22	-0,17	-0,38
1600	-0,39	-0,17	-0,16	-0,36
2000	-0,32	-0,11	-0,12	-0,28
2500	-0,20	-0,01	-0,02	-0,18
3150	-0,01	0,08	0,06	0,02
4000	0,25	0,30	0,24	0,24
5000	0,63	0,61	0,42	0,51
6300	1,21	1,02	0,78	0,91
8000	2,13	1,83	1,12	1,19
10000	2,89	2,00	1,07	0,86
12500	1,09	1,01	0,08	0,03

Table 1: Four GRAS 40 PS initial factory calibration frequency response norm. @ 250 Hz.

3.2 Frequency Response Comparison

Applying the IEC 61094-5 comparison jig technique with the proper adaptations, as described in item 2, lead to the frequency responses exhibited in Chart 1.

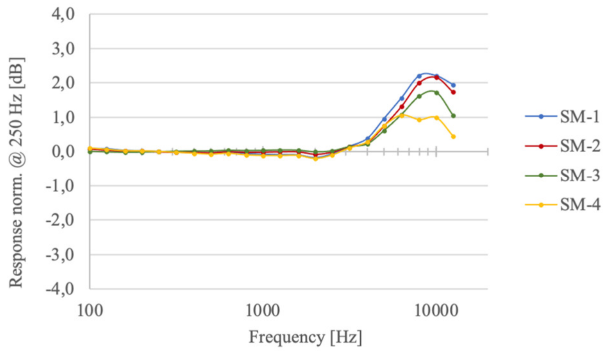

Chart 1: Four GRAS 40 PS calibration frequency response norm. @ 250 Hz by IEC 61094-5 comparison jig technique.

The method used for this comparative was the well-known Normalized Error (NE), according to Equation 1.

$$NE = \frac{|S_{cj} - S_{fc}|}{\sqrt{(U_{cj})^2 + (U_{fc})^2}}$$

Equation 1: Normalized Error.

Where *S* are the sensitivities in dB re. 1 V/Pa, *U* is the associated uncertainty in dB, *cj* stand for the values of the comparison jig, and *fc* of the factory calibration. For the frequency response, the values of *S* were normalized at 250 Hz, so just the merit of the frequency response could be evaluated, that is, without the influence of the difference of absolute sensitivities. Also, it is good to recall that as the manufacturer did not express its own uncertainty, for the effects of this work *Ucj* is equivalent to *Ufc*. When EN < 1, the comparing is said to be compatible.

It is proper to mention that this data was obtained in 2021, and the surface microphones were in use in the automotive industry. Hence, it was already expected some difference due to time and wear of the transducers. Conversely, the frequency response comparative was compatible for the whole frequency range, as shown in Table 2. Regarding the uncertainty, this work adopted a conservative approach, taking a typical uncertainty for IEC 61094-5 calibrations with 0,1 dB precision, and enhancing it by 50% in the more controlled frequencies, namely up to 8 kHz, and doubling it for frequencies from 8 kHz onwards. The concern with higher frequencies is especially due to the presence of the protective grid, that has increasing influence as frequency rises.

Freq [Hz]	SM-1 NE	SM-2 NE	SM-3 NE	SM-4 NE	U [dB]
100	0,7	0,5	0,6	0,5	0,3
125	0,3	0,4	0,5	0,4	0,3
160	0,3	0,3	0,4	0,4	0,3
200	0,1	0,1	0,2	0,1	0,3
250	0,0	0,0	0,0	0,0	0,3
315	0,2	0,1	0,2	0,2	0,3
400	0,3	0,2	0,3	0,3	0,3
500	0,4	0,3	0,4	0,3	0,3
630	0,5	0,5	0,5	0,4	0,3
800	0,6	0,5	0,5	0,4	0,3
1000	0,6	0,5	0,5	0,5	0,3
1250	0,8	0,5	0,5	0,6	0,3
1600	0,7	0,4	0,5	0,6	0,3
2000	0,3	0,1	0,3	0,2	0,3
2500	0,3	0,0	0,1	0,2	0,3
3150	0,4	0,2	0,2	0,2	0,3
4000	0,3	0,1	0,0	0,1	0,3
5000	0,8	0,3	0,5	0,6	0,3
6300	0,8	0,7	0,7	0,4	0,3
8000	0,1	0,2	0,6	0,3	0,6
10000	0,8	0,2	0,8	0,2	0,6
12500	0,8	0,6	0,9	0,4	0,8

Table 2: NE values for normalized frequency response @ 250 Hz.

Despite not founding considerable difference in the frequency response, the absolute sensitivity itself has some remarkable discrepancies, as seen in Table 2.

	SM-1	SM-2 [dB re. 1 V/Pa]	SM-3	SM-4
FC	-46,91	-46,67	-47,09	-46,78
CJ	-45,99	-47,37	-46,20	-48,30
NE*	2,2	1,6	2,1	3,6

Table 2: Four GRAS 40 PS sensitivity at 250 Hz and compare by Normalized Error (*U = 0,3 dB)

It should also be considered that the differences could be due to the distinct methods used for this sensitivity determination. Whereas with the comparison jig the sensitivity it is a natural outcome with no additional concerns, using a pistonphone requires a thorough reliability on the accessories used, a very delicate issue, once there are many variables not strictly controlled.

3.3 A Free-field calibration attempt

Even though the GRAS 40PS is a pressure-field surface microphone, an attempt of an IEC 61094-8 free-field calibration by means of a TST was proceeded using the same positioning logic of the adaptation to the comparison jig. The microphone was once again affixed with a double-sided tape on the tip of a ½" damaged microphone and positioned in the same geometrical spot that the reference was before. Both microphones were 1 m away from the sound source that provided a frontal incidence, with no reflection surfaces nearby that could not be eliminated by windowing in the subsequential signal processing. This is the exact same procedure used for any other microphone. The results comparing the free-field and pressure field responses for two of the microphones are found in Chart 2.

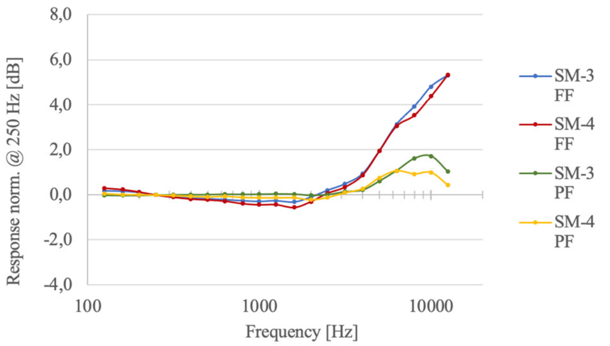

Chart 2: Two GRAS 40 PS pressure-field and free-field frequency response norm. @ 250 Hz.

The chart shows that the free-field calibration yielded an expected result, to wit, a positive correction factor to higher frequencies is something natural to pressure-field microphones. Nevertheless, the effects of the protection grid and the cable positioning in relation to the capsule point out to a need of enhancing uncertainty in this modality, even more than with pressure-field techniques. Still, it is exciting to be aware of the possibility to apply this method, once when disposed at 90º in relation to the sound source, it could also be a means to determine pressure-field frequency response and absolute sensitivity.

4. CONCLUSION

The results of this work indicate that, in fact, the comparison jig technique described in IEC 61094-5 can be successfully used for periodic tests and calibrations of surface microphones. The NE values were compatible in the whole range for each and every one of the samples, even considering that the sensitivity values certainly have shifted in this 10 years use, specially for higher frequencies. This could open the way to further study and even future revisions of the IEC 61094-5, considering embracing this kind of microphone to its content or even the elaboration of another part of this standard series hosting all of the possible means to calibrate them. This certainly would add reliability to this type of transducer that is common in critic industries as automotive and aeronautic.

However, the differences found in absolute sensitivity should inspire caution and further studies. It would be odd that those microphones, with stable responses even at higher frequencies, to have shifted that much in absolute sensitivity. The most probable scenario is that the accessories and coupling methods to use sound level calibrators and pistonphones as references to determine surface microphone's sensitivities are more vulnerable that one could expect. On the other hand, the comparison jig technique does not have many variables that could make it err in this proportion regarding sensitivity values, as it is a natural outcome of the method.

Finally, the possibility of using free-field methods could also be further studied as one of the ways of calibrating a surface microphone. Although this method is more complex and requires facilities that are more specialized, it is still an option.

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