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In-plane excitation of reception plates according to EN 15657:2017

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Abstract
EN 15657:2017 [1] describes methods for the determination of the characteristic structure-borne sound power of building service equipment. The so-called indirect method is based on the use of a reception plate. The method is robust for the case when the mobility of the source (building service equipment) is significantly higher than the mobility of the reception plate. The source is mounted on the plane of the reception plate. Therefore the excitation of the reception plate happens *out-of-plane*, the measurement is carried out by sensors sensitive to the component of the *out-of-plane* movement of the plate. In practice however there are situations which require the mounting of the source in wall openings, for example roller shutters in window openings or doors. In these cases the excitation happens in the soffit of the structures, the excitation takes place *in-plane*. The assumption then is that primarily quasi-longitudinal waves rather than bending waves are excited in the receiving building elements, but then a fast conversion of energy from quasi-longitudinal waves to bending waves takes place. A determination of the characteristic structure-borne sound power should then be possible as in the usual case of an out-of-plane mounting. To test this assumption the *in-plane* exitation of two reception plates was experimentally investigated.

Keywords: Structure-borne Sound, Reception Plate, In-Plane Excitation

1 INTRODUCTION

In the actual version of the German Standard on sound insulation in buildings DIN 4109-1:2018-01 [2] requirements on the A-weighted, maximum and normalized sound power level $L_{\text{AF,max,n}}$ caused by service equipment are listed.

In order to predict this level in rooms of interest during the planning phase there is a model available in the harmonized European Standard EN 12354-5:2009 [3]. As input data the charateristic structure-borne sound power P_{sn} of the individual service quipment is needed. In the European Standard EN 15657:2017 [1] a measurement procedure using a reception plate to obtain P_{sn} is described. There the service equipment is installed directly on the front of the reception plate, the exitation of the reception plate takes place *out-of-plane*.

In fact it is often the case that the service equipment is not installed on the front, but inside the building element like e.g. windows or ventilators in walls or roller shutters in the soffit of the window-like opening within a wall. Therefore one can assume that the exitation of the reception plate resp. building element takes place *in-plane*. In order to study the applicability of the reception plate method according to [1] a reception plate test rig was set up in the new Rosenheim technology center for energy & buildings (roteg) at the Technische Hochschule Rosenheim. The reception plates are in agreement with the example described in [1], but have differing geometries. One of the recpetion plates has an opening with size of 1.50 m x 1.25 m. Within this opening service equipment can be installed und run under realistic mounting conditions if the equipement has to be installed in the soffit. The reception plate test rig is shown in figure 1; the test rig is built up in accordance with the sketch of appendix F in [1].

In order to extend the measurement method of the charateristic structure-borne sound power P_{sn} to an in-plane exitation, several investigations were carried out. First of all the driving-point mobility was determined for

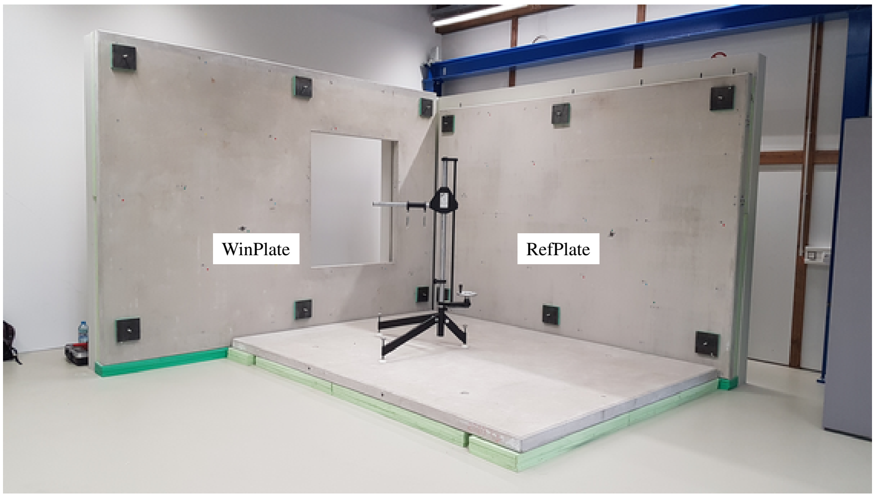


Figure 1. Reception plate test rig at roteg. The reception plate with an window opening is refererred to *WinPlate* in the text, the normal reception plate according to [4] is named *RefPlate*.

in-plane and *out-of-plane* exitation of the reception plates. Secondly the balance of the input power at the excitation point and the power of the reception plate was compared.

2 RECEPTION PLATE METHOD

According to the Standard EN 15657:2017 [1] the reception plate method is called an indirect method to determine the characteristic structure-borne sound power of a device, since it is not determined directly at the device, but by the vibrational energy of the reception plate, where it is mounted on. The installation of the device on the recpetion plate is done as it is on the building site and the device is then driven under typical operation conditions. In parallel the spatial average of the square of the plate velocity $\tilde{v}_i^2$, is measured using N accelerometers on the reception plate. Taking into account the loss factor η and the toal mass m of the reception plate, the installed structure-borne sound power of the device can be determined according equation (1)

$$P_{\mathrm{s}} = m \cdot \eta \cdot \omega \cdot \frac{1}{\mathrm{N}} \cdot \sum_{i=1}^{\mathrm{N}} \tilde{v}_i^2 \tag{1}$$

The loss factor is usally determined by a measurement of the structure-borne reverberation time, or in the low frequency range with a low mode density by determining the width of the eigenmodes.

The characterisitic structure-borne sound power is calculated using equation (2), mutliplying the measured structure-borne sound power of the reception plate P_{s} by the ratio of the single-euivalent driving-point mobility $Y_{\mathrm{R,low,eq}}$ of the plate from the mean of all excitation points and the charateristic mobility of an infinte plate $Y_{\mathrm{R},\infty,\mathrm{low}}$.

$$P_{\mathrm{sn}} = P_{\mathrm{s}} \cdot \frac{Y_{\mathrm{R},\infty,\mathrm{low}}}{\mathrm{Re}(Y_{\mathrm{R,low,eq}})} \tag{2}$$

The recpetion plate method is rather robust in the case that the mobility of the reception plate is much smaller than the mobility of the source. To emphasize this condition the index *low* is added.

Due to the normalization according to equation (2) the characteristic structure-borne sound power of different devices of the same type can be compared, even when the devices have been measured on different reception plates.

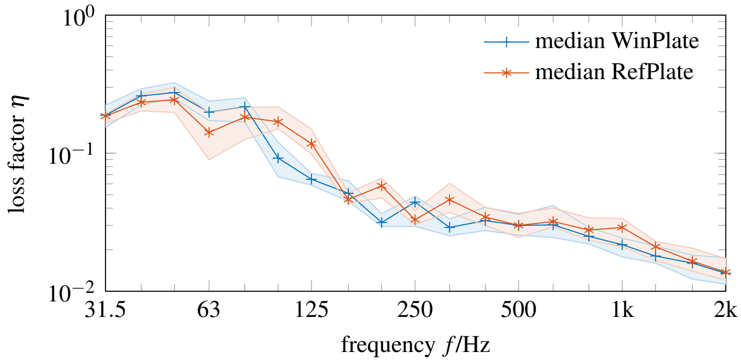


Figure 2. Loss factors of the *RefPlate* and the *WinPLate*; presented are the median and the 25 % and 75 % quantils.

3 LOSS FACTORS AND MOBILITIES OF THE RECEPTION PLATES

The loss factors of the reception plates have been measured by using the reverberation time method. The measurement results of the loss factos are shown in figure 2. The results are averaged from three exitation positions, twelve randomly chossen measurement positions, the evaluation of the results was carried out using Schroeder backward integration and evaluating T_{10}. The exitation was done by an impact hammer. Due to the high damping of the elastomer layers supporting the two plates, the loss factors are quite high. By an experimental modal analysis it was confirmed that at least one bending mode is within each 1/3-octave band. The small spreading of the measurement results gives rise to be confident in the procedure and in the numbers.

The characteristic mobility of an infinite plate, exited *out-of-plane* is given by equation (3) with bending stiffness B according to equation (4), density ρ and plate thickness t [5]. It is frequency indipendent and pure real. The index *oop* indicates *out-of-plane* exitation. The reception plates have a thickness of 10 cm, the size of the *RefPlate* is 3,8 m x 2.7 m and of the *WinPlate* 4,0 m x 2.8 m, the density ρ was determined to $2600(1 \pm 2\%)$ $\mathrm{kg/m^3}$, the Poisson ratio ν was chosen to be 0.2, the used value for the elasticity modul E was determined from a TOF-measurement of the longitudinal wave and from the first logitudinal eigenmode as $47(1 \pm 12\%)$ GPa. However for further comparisons values from literature are taken (E = 30 GPa, ρ = 2300 $\mathrm{kg/m^3}$). In the Standard EN 15657:2017 [1] the characteristic mobility of an infinite concrete plate of a thickness of 10 cm is given to $Y_{\mathrm{R},\infty,\mathrm{low}} = 5 \cdot 10^{-6}(\mathrm{m/s})/\mathrm{N}$. It can be calculated using equation (3).

$$Y_{\infty,\mathrm{oop}} = \frac{1}{(8 \cdot \sqrt{\rho \cdot t \cdot B})} \tag{3}$$

$$B = \frac{E \cdot t^3}{12 \cdot (1 - \nu^2)} \tag{4}$$

The values of the driving-point mobility of the different plates were obtained by an excitation of the plates at three points, indicated in figure 4a for the *RefPlate* and in figure 4b for the *WinPlate*. The measurements consisted of an average of approx. five hits at each excitation point, averaging the mobilities of the two accelerometers next to the hammer position as shown in figure 3. In fact the mobility at each individual excitation point was determined from the cross spectrum of force and velocity and the autopower spectrum of the force. The magnitudes of the complex narrow band mobilities had then be converted to one-third octave band values and averaged for all excitation points. The magnitudes Y_R of these averaged driving-point mobilities are indicated with an index *av* and an index *oop* for out-of-plane excitation and *ip* for in-plane excitation.

Looking at figure 5 it can be noticed that in the case of *out-of-plane* excitation the agreement of $Y_{\mathrm{R,av,oop}}$ with $Y_{\infty,\mathrm{oop}}$ is quite good for both reception plates, especially above 100 Hz. On a logarithmic scale the deviation is less than 3 dB.

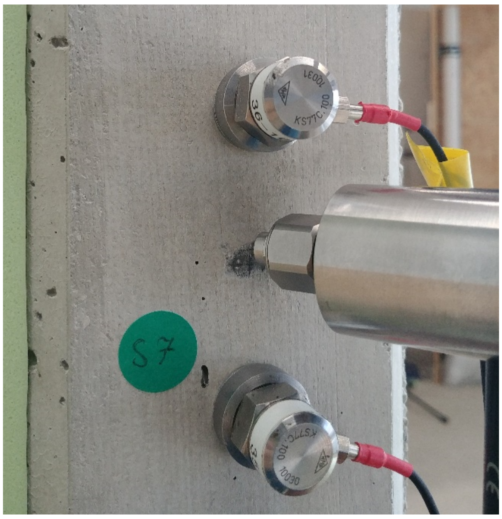


Figure 3. Force excitation with an impact hammer and two accelerometers for the determination of the velocity. The situation shown is the in-plane exitation, where the accelerometers are mounted in the middle plane of the plate.

The characteristic mobility of an infinite plate, excited *in-plane*, is given by equation (5) [6] with shear stiffness G, longitudinal stiffness D, plate thickness d and the wave numbers for quasi-longitudinal and transverse waves k_{L} and k_{T}. Parameter e corresponds to the radius of the indenter. It was measured by colouring the tip of the impact hammer and determining the size of the imprint to $e = 2\,\mathrm{mm}$.

$$\underline{Y}_{\infty,\mathrm{ip}} = \frac{\omega}{8 \cdot t \cdot D}\left[1 - \mathrm{i}\frac{2}{\pi}\ln\frac{k_{\mathrm{L}} \cdot e}{2}\right] + \frac{\omega}{8 \cdot t \cdot G}\left[1 - \mathrm{i}\frac{2}{\pi}\ln\frac{k_{\mathrm{T}} \cdot e}{2}\right] \tag{5}$$

$$G = \frac{E}{2 \cdot (1+\nu)} \tag{6}$$

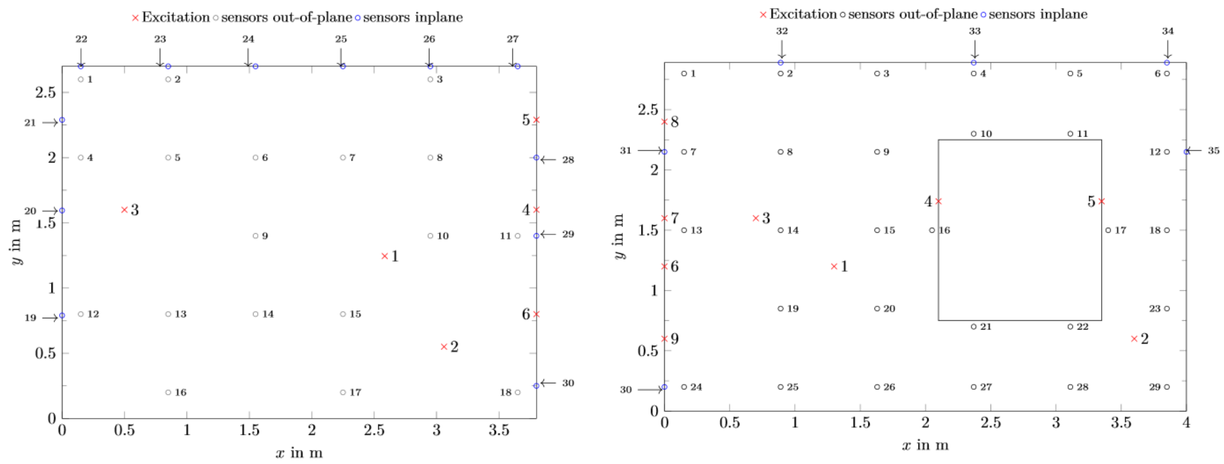
$$D = \frac{E}{(1-\nu^2)} \tag{7}$$

$$k_{\mathrm{L}} = \sqrt{\frac{\rho \cdot (1-\nu^2)}{E}} \cdot \omega \tag{8}$$

$$k_{\mathrm{T}} = \sqrt{\frac{2 \cdot \rho \cdot (1+\nu))}{E}} \cdot \omega \tag{9}$$

The values of the driving-point mobility for *in-plane* excitation of the plates were obtained at three resp. five different points distributed along the vertical face as shown in figure 6.

Figure 5a shows a comparison of the measured mobilities $Y_{\mathrm{R,av,ip}}$ and the theoretical curve according to equation (5). As in the case with *out-of-plane* excitation there is good agreement of the measured mobilities with the mobility $Y_{\infty,\mathrm{ip}}$ of an infinite plate above 100 Hz. At lower frequency the mobilies tend to higher values. This is due to the elastic bearing of the reception plate, which together with the plate forms a mass-spring-system. Its resonance is at approx. 30 Hz. The decline of the mobilities from the resonance towards higher frequeny is the mass dominated part of the resonance. In the case of the *WinPlate* the *in-plane* excitation was carried out in horizontal as well as vertical direction. For the vertical direction only one excitation point and one accelerometer position could be measured since the coherence was bad between the one-third octave bands 160 Hz and 200 Hz. Therefore no results are shown in this frequency range. Also the mass-spring system is different for horizontal and vertical *in-plane* excitation, this explains the difference in the low frequency range.



(a) *RefPlate*

(b) *WinPlate*

Figure 4. Excitation positions, marked with red crosses - positions 1..3 are out-of-plane exitations, positions 4..6/9 indicate in-plane exitation. Measurement positions of the accelerometers are marked with black circles for out-of-plane measurements and with red circles for in-plane measurements.

For the *RefPlate* the measured mobility shows a distinct resonance at approx.500 Hz, indicated as a black vertical line in figure 5a. This is the fundamental mode of the longitudinal waves. It can be identified also in the case of the *WinPlate* with vertical excitation, but at a higher frequency due to smaller dimensions. It is not that evident for the horizontal excitation of the *WinPlate*, since the window opening supresses this standing wave.

4 POWER BALANCE

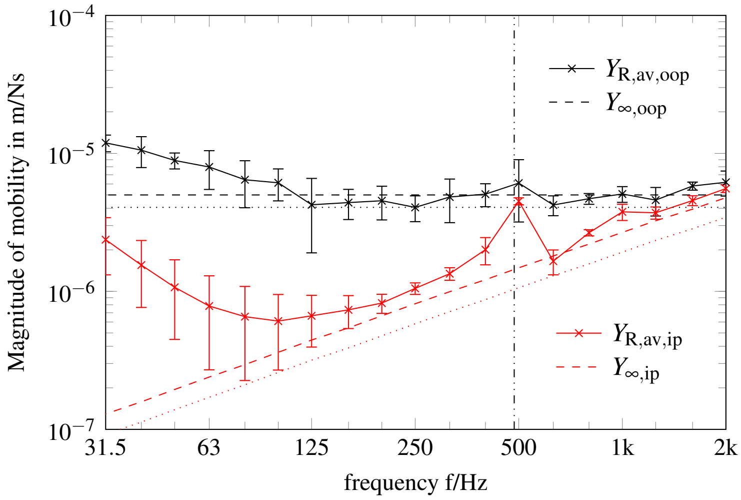
The basic assumption of the reception plate method is expressed in equation (1). The power of the plate P_s equals the power input at the excitation point P_ep. The latter is evaluated according to (10). It is calculated from the real part of the cross spectrum of force and velocity. Figure 3 shows the measurement setup for the presented investigations, where the source is realized by the impact hammer.

$$P_\mathrm{ep} = \frac{1}{2}\mathrm{Re}\left\{\underline{\hat{F}}^* \cdot \underline{\hat{v}}\right\} \tag{10}$$

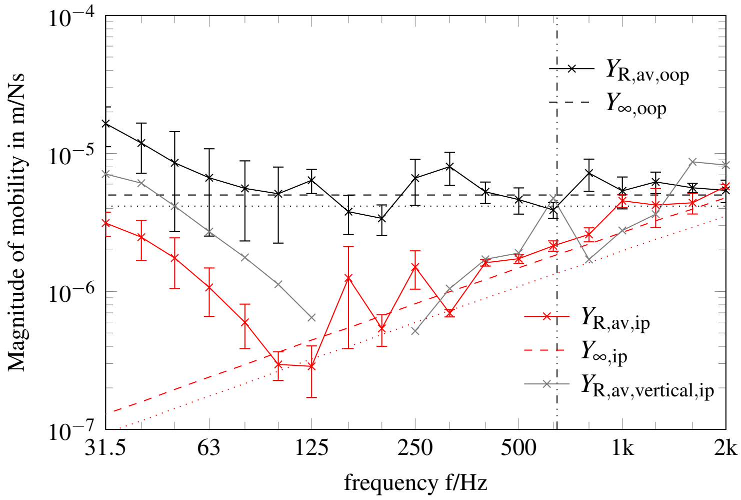
In figure 6a and 6b level differences are shown for various combinations of excitation and measurement directions. The level differences ΔL_Ws indicate the difference between the direct measured power at the excitation point P_{ep} and the power of the reception plate P_s.

The level difference has been calculated as average of three individual excitation positions for *out-of-plane* excitation. The standard deviation is indicated with error bars. The power balance does hold for the case of *out-of-plane* excitation und measurement of the *out-of-plane* power of the reception plate P_s in both cases, shown in figure 6a, graph **a** for the *RefPlate* and in figure 6b, graph **a** for the *WinPlate*. Level differences are below 3 dB.

The power balance does not hold in the case of an *in-plane* excitation und measurement of the *out-of-plane* power of the reception plate P_s. In both cases level differences exceed values of 10 dB in a wide frequency range, as can be seen in figure 6a, graph **b** for the *RefPlate* and in figure 6b, graph **b** for the *WinPlate* . *In-plane* excitation was carried out at three excitation positions for each reception plate. Obviously the input *in-plane* power is not converted to bending waves at all but remains as quasi-longitudinal waves in the plate, at least within the measurement time intervall. The reason that the level differences are less for the *WinPlate*

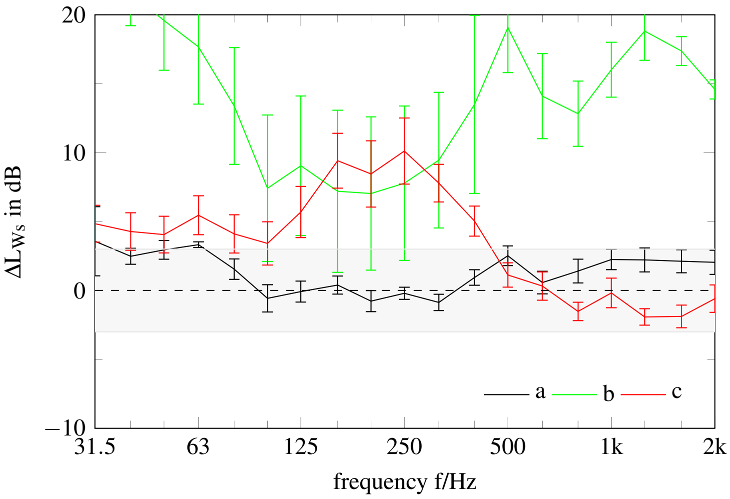


(a) *RefPlate*

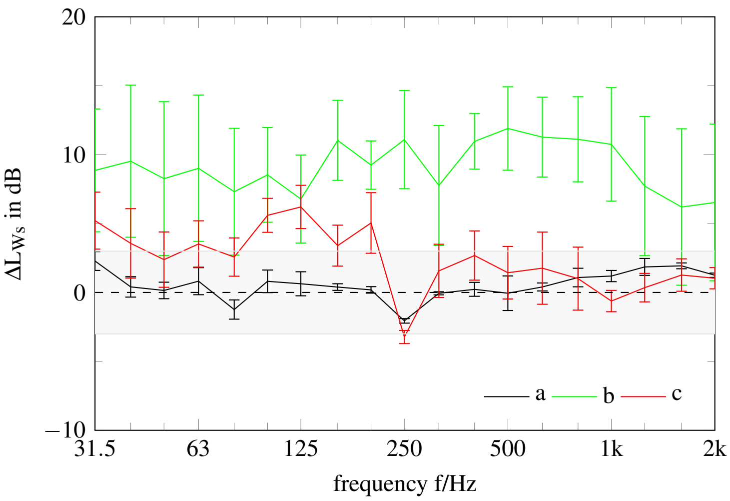


(b) *WinPlate*

Figure 5. Magnitude of the averaged driving-point mobilities for an excitation *out-of-plane* (oop) or *in-plane* (ip). Indicated with dashed lines are also the theoretically expected values for infinite plates. Dotted lines indicate the theoretical values, when the calculation is performed with the measured material data. Error bars indicate the standard deviation of the magnitudes from different exitation positions.



(a) *RefPlate*



(b) *WinPlate*

Figure 6. Level difference ΔL_{Ws} of P_{ep} and P_s; mean value of three excitation positions together with their standard deviation, indicated by error bars.
a: oop excitaion, oop measurment (standard case according to EN 15657:2017 [1])
b: ip excitation, oop measurement
c: ip excitation, ip measurement

(approx. 10 dB over the whole frequency range) may be due to the fact, that the discontinuities at the window opening contributes to a conversion of quasi-longitudinal waves into bending waves.

A much better power balance can be observed by comparing the input power of *in-plane* excitation with the *in-plane* power of the reception plate determined by the accelerometers, which are sensitive to *in-plane* movement of the plate. This can be seen from the graphs in figure 6a, graph **c** for the *RefPlate* and in figure 6b, graph **c** for the *WinPlate*. Especially above the fundamental longitudinal mode, the power balance is quite good with differences within 3 dB. This supports the conclusion that energy is stored in longitudinal standing waves and is therefore not detected by *out-of-plane* measurement.

5 SUMMARY

The reception plate method according to EN 15657:2017 [1] was investigated on the extension to an in-plane excitation. The magnitudes of the measured driving-point mobilities show a very sensible behaviour, their spectral shape can be explained to a satisfactory extent.

The power balance between the input power at the excitation point and the reception plate power as the fundamental requirement for the application of the reception plate method is achieved for the case in which the reception plate is excited *out-of-plane*. In this case dominantly bending waves are excited, which can be measured by *out-of-plane* sensitive accelerometer.

However the power balance is not fulfilled to a satisfactory extent if the excitation of the reception plate is *in-plane*. The correct determination of the reception plate power in this case needs further investigations.

6 ACKNOWLEDGEMENTS

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