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A MODAL APPROACH FOR REVERBERATION TIME MEASUREMENTS IN NON-DIFFUSE SOUND FIELD

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In recent years the extension of reverberation time measurements to frequencies below 100 Hz is becoming more and more important due to the increase of low frequency sources. In ordinary rooms with volumes smaller than 200 m^3 the low frequency sound field is non-diffuse due to the presence of modes, which are also the main cause of bad quality of listening in terms of clarity and rumble effects. Since standard measurements according to ISO 3382 fail to achieve accurate and precise values in third octave bands due to non-linear decays of room modes, a new approach based on reverberation time measurements of single resonant frequencies (the modal reverberation time) is introduced. Two measurement methods based on the relation between modal decays and resonant half bandwidths are proposed: the direct method, based on the direct evaluation of modal sound decays with interrupted source signals, and the indirect method based on half bandwidth measurements. Proper measurement procedures, with microphones placed at rectangular room corners and anti-resonant sine waves and sweep source signals for direct and indirect measurement methods respectively, are proposed. Comparison between direct and indirect methods shows good and significant agreement. Comparing modal reverberation times with standard ones, the inadequacy of standard procedure to get accurate and precise values at low frequencies with respect to the modal approach becomes evident. In the future, further investigations are necessary in more rooms to improve uncertainty evaluation.

1. Introduction

This paper is a brief version of the article “Reverberation time measurements in non-diffuse acoustic field by the modal reverberation time” published on journal in March 2016 [1].

In the last years, the increase of low frequency sources suggested to extend building acoustics measurements to frequencies below 100 Hz [2-3]. At such frequencies, especially between 50 Hz and 100 Hz, and in ordinary rooms the sound field is non-diffuse due to the presence of modes, which entail large sound pressure level fluctuations in space and frequency domains. At resonant frequencies, amplitudes are wider and decays are much longer, causing uneven tonal quality, interference with clarity and rumble effects, and noise from other environments [4-10]. For this reason accurate measurements of reverberation time at low frequency are necessary in order to perform the acoustic treatments of listening and working rooms. Standard reverberation time measurement in ordinary dwellings is reported in IS0 3382-2:2008 [11], which is applied from 100 Hz to 5000 Hz. A procedure for frequencies below 100 Hz is not reported, since the diffuse field approach is not suitable. At such frequencies, sound decay curves may not be approximated by a straight line but depend on room modes that fall in that particular octave or third octave band, and on the interaction between them, entailing a non-linear sound decay [12]. Such condition involves high measurement

uncertainties (percentage relative standard deviations are in the order of 20% - 60%) and thus inaccurate and imprecise reverberation time values [13-15].

Given such evidences, a new and more suitable measurement method that describes the reverberation time at low frequencies is investigated in this work. The peculiarity of non-diffuse nature of sound field at low frequency in small ordinary rooms suggests to move from the classical standard approach based on third octave bands measurements, to a modal approach, based on reverberation time measurements of single resonant frequencies: *the modal reverberation time* (T_n).

2. Background theory

From background theory, modal reverberation time can be measured with two different methods: the direct method, based on standard guidelines for interrupted signal method, but with different source/receiving positions and source signals; the indirect method, based on half bandwidth measurement of resonant modes, which is related to the modal damping and, as a consequence, to the modal reverberation time.

Considering a room with reactive surfaces and dissipative properties, it is supposed to supply energy to a resonant system through a sound source emitting a sinusoidal signal at a resonant frequency. When the source emission is interrupted, at time t=0, wave continues its path: part of its energy is reflected by the walls, and another part is dissipated by the boundary walls and the air in the room. The squared sound pressure decay of a single nth mode, proportional to its energy, can be written as

$$p^2(t) = p^2(0)\exp(-2\delta_n t) \tag{1}$$

where δ_n is the decay constant of the nth mode, or the modal damping constant [16] and gives information about the half bandwidth of the resonant frequency Δf_{-3dB} according to

$$\Delta f_{-3dB} = \frac{\delta_n}{\pi} \tag{2}$$

In order to evaluate the reverberation time of a single mode after a decay of 60 dB, the following formulations are obtained:

$$\begin{aligned} &L(T_n) - L(0) = 10\ log_{10}\left(\frac{p^2(T_n)}{p^2(0)}\right) = -60\ dB; \\ &\left(\frac{p^2(T_n)}{p^2(0)}\right) = \exp(-2\delta_n T_n) = 10^{-6}; \\ &2\delta_n T_n = 6\ \ln(10); \\ &\Delta f_{-3dB} = \frac{\delta_n}{\pi} = \frac{3\ \ln(10)}{\pi\ T_n} = \frac{2.2}{T_n} \end{aligned} \tag{3}$$

and so the modal reverberation time of a single mode can be expressed by

$$T_n = \frac{2.2}{\Delta f_{-3dB}} \tag{4}$$

In this way a direct relation between the resonant half bandwidth and the modal reverberation time is obtained. Such result allows to perform an indirect measurement of modal reverberation time through the evaluation of the resonant half bandwidth.

3. Experimental measurements

First measurements were performed in the receiving room of the impact sound insulation laboratory at INRIM which is completely empty and has a rectangular shape with dimensions L_x= 4.02 m, L_y=3.64 m, L_z=3.45 m. Concrete walls are completely bare as well as the inner volumetric space. The measurement chain is composed as follows: 1/2" microphones, closed-box loudspeaker with a 15-inch cone in order to generate suitable low frequency sound pressure levels, power amplifier, 24-bit A/D converter, spectrum analyzer. Measurements have been limited to an empty test room such as an impact sound insulation laboratory, because it is characterized by a strong non-diffuse field due to the lack of furniture or bass traps. Furthermore it is geometrically representative of ordinary rooms and is acoustically insulated from outside. In this way, it was possible to evaluate the pure modal acoustic response of the room, considering only damping of boundary walls.

3.1 Standard approach: ISO 3382 method

Reverberation time measurements at low frequencies with interrupted noise method according to ISO 3382 were performed in the test room (3 microphone positions, 2 source positions, 2 repetitions) in order to have a first comparison and reference with standard procedure. Results are reported in Table 1. As mentioned above, the presence of different modes in a low frequency third octave band entail non-linear decays. An example for 50 Hz third octave band is shown in Fig. 1.

Table 1: Low frequency reverberation times measured according to ISO 3382 in the empty test room. Means and standard deviations refer to the 12 spatial measurements.

f / Hz	$\overline{T}$ / s	$s(T)$ / s
50	7.49	1.89
63	4.32	0.59
80	3.83	0.39
100	2.63	0.29

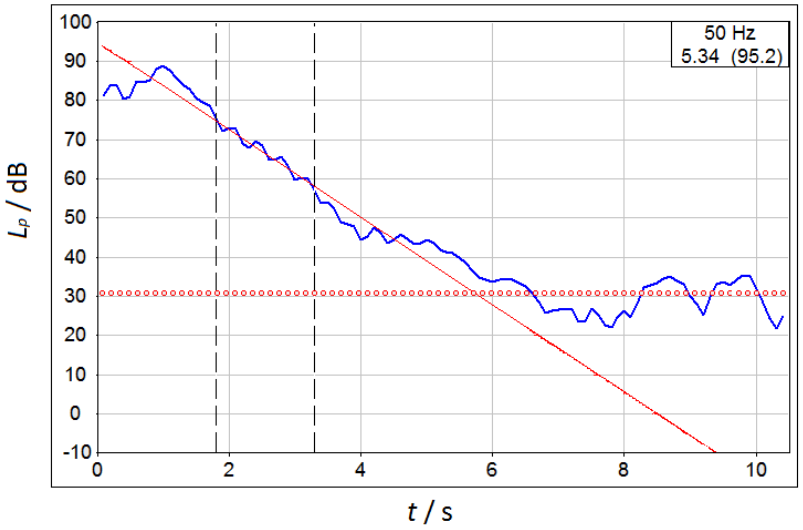

Figure 1: Example of non-linear decay of 50 Hz one-third octave band with standard measurement.

3.2 Modal approach: direct and indirect methods

The new modal approach is based on the decay of individual resonant frequencies (f_n) of rectangular rooms, or modal reverberation times, instead of one-third octave band analysis required by ISO 3382. Two measurement methods, derived from background theory, were experimentally evaluated: the first is the direct method, based on the interrupted signal method, but with different

measurement positions and source signals with respect to ISO Standard. Such method, which directly evaluates sound decays, is considered as the reference for accuracy. The second is an indirect method based on resonant half bandwidth measurements. This is the first experimental verification of Eq. (4). Two different source signals were also evaluated.

3.2.1 Direct method

Direct measurement of modal reverberation time were performed with the interrupted noise method, acquiring waterfall spectra with sound source and microphone placed at two different corners. Since it was not possible to directly determine the T_{60}, due to the impossibility to have a sufficient signal-to-noise ratio, in most of cases, T_{30} and, in few cases, T_{20} were evaluated. In a first step, spatial measurements were neglected as the main goal was to determine the most suitable sound source signal. Different signals were tested: pink noise, resonant sine waves (47.5 Hz and 63.5 Hz) and anti-resonant sine waves (56 Hz and 75 Hz). Pink noise signal showed problems of unstable spectra due to its random nature (Fig. 2). Whereas, clean and clear spectra were obtained with sinusoidal signals. In such condition the room-system is forced to resonate at a specific frequency: at the beginning, when few energy is supplied, the system vibrates according to its resonant frequencies (transient state). With the increase of supplied energy in time, the system is unable to redistribute energy to its modes, but is forced to resonate at the driving frequency (stationary state). Once the signal is interrupted, the system redistribute energy according to its modes and dissipates with time. Such behavior allows to obtain clear decays. In a first step, resonant sine waves were generated. Unfortunately, with such source signals, loudspeaker membrane was damped by the modal sound field generated at that resonant frequency, entailing a distortion in the modal behavior of the room. In order to avoid this problem, two anti-resonant sine waves, far enough from closer modes, were tested (56 Hz and 75 Hz). Resulting decays are clearer (Fig. 3) and interferences between the modal field and the loudspeaker are avoided.

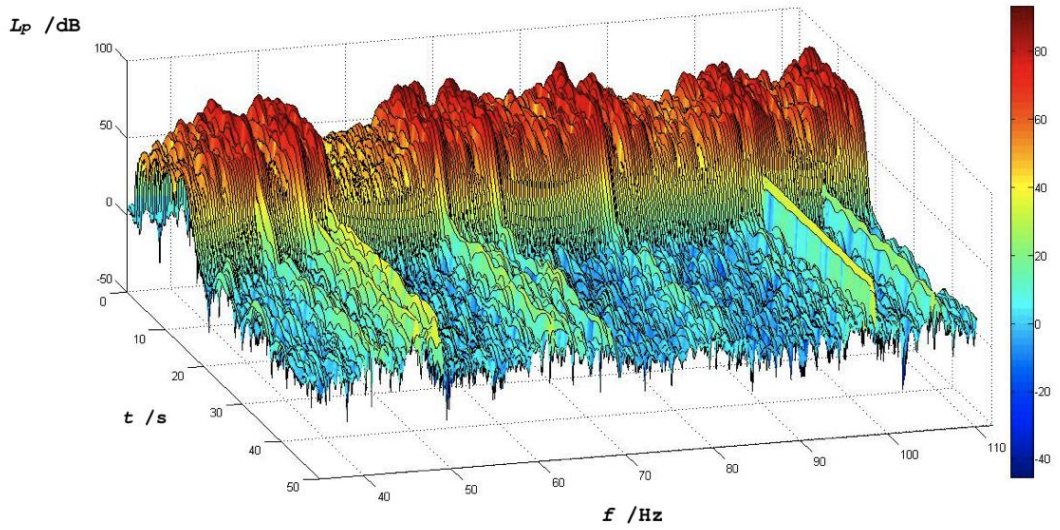

Figure 2: Modal decays with pink noise.

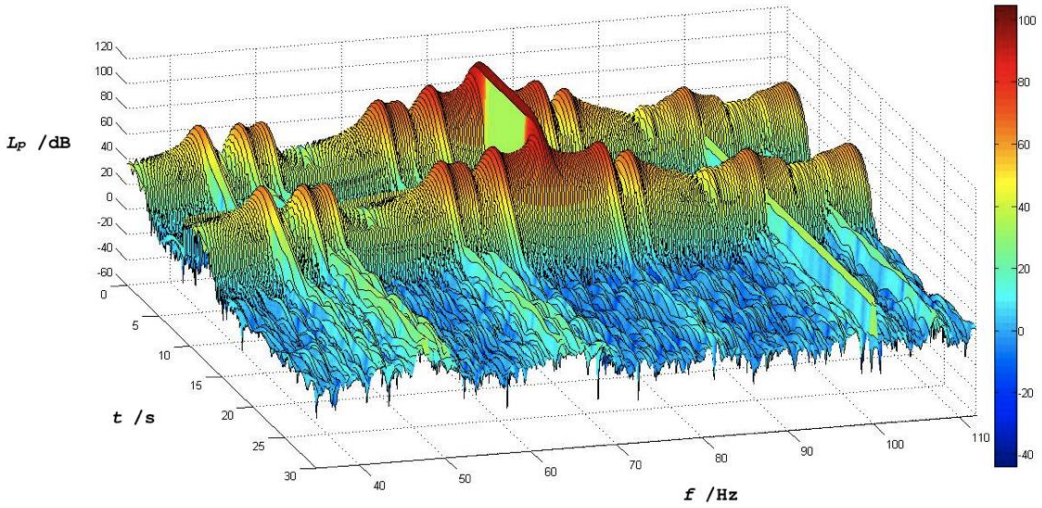

Figure 3: Modal decays with 75 Hz anti-resonant sine wave.

Table 2: Direct modal reverberation times with pink noise and anti-resonant sine waves (56 Hz and 75 Hz).

f_n /Hz	*Source signal*	T_n/s	s_{res} /dB	f_n /Hz	*Source signal*	T_n / s	s_{res} /dB	f_n /Hz	*Source signal*	T_n / s	s_{res} /dB
42.5	56 Hz	7.67	0.13	63.5	56 Hz	3.17	0.51	82	56 Hz	3.24	0.45
	75 Hz	7.51	0.32		75 Hz	2.89	0.68		75 Hz	3.21	0.21
	Pink	6.43	0.76		*Pink*	3.49	0.72		*Pink*	3.33	0.49
47.5	56 Hz	4.38	0.46	66	56 Hz	2.25	2.76	85.25	56 Hz	2.91	1.14
	75 Hz	4.27	0.76		75 Hz	2.46	1.86		75 Hz	2.74	1.11
	Pink	4.19	0.45		*Pink*	1.89	5.65		*Pink*	2.53	2.30
50	56 Hz	3.66	0.42	69.5	56 Hz	3.58	0.26	99.25	56 Hz	2.73	3.27
	75 Hz	4.08	0.59		75 Hz	3.39	0.07		75 Hz	2.03	1.86
	Pink	7.03	2.63		*Pink*	3.53	0.50		*Pink*	2.81	2.40

Modal reverberation times obtained with pink noise are slightly different with respect to the ones achieved with anti-resonant sine waves. Residual standard deviations of linear fit (s_{res}) are lower for anti-resonant sine wave signal, on average (Table 2). Furthermore, since the 75 Hz anti-resonant sine wave is located in the central part of the spectrum and does not influence adjacent modes, it is considered as the reference source signal for direct method.

3.2.2 Indirect method

Modal reverberation times were also evaluated by half bandwidth measurements of resonance peaks according to Eq. (4). Thus, no decay measurements were performed. Half bandwidths were obtained by spectrum measurements (resolution of 0.1 Hz). Also in this case, loudspeaker and microphone were placed at two corners of the room to maximize the modal acoustic response and signal-to-noise ratios. Two different source signals were tested: a pink noise and a sweep signal (Fig. 4). Spectrum obtained with the sweep signal is smoother and resonance peaks are well defined compared to pink noise one. Half bandwidths of resonance peaks were then calculated through the implementation of the best fit with a Lorentzian function. Modal reverberation times evaluated with both signals are reported in Table 3. Resonance peaks measured with sweep signal are well defined and the Lorentzian fit is more precise since residual standard deviations are lower. For this reason, sweep source signal can be considered as the reference for indirect method.

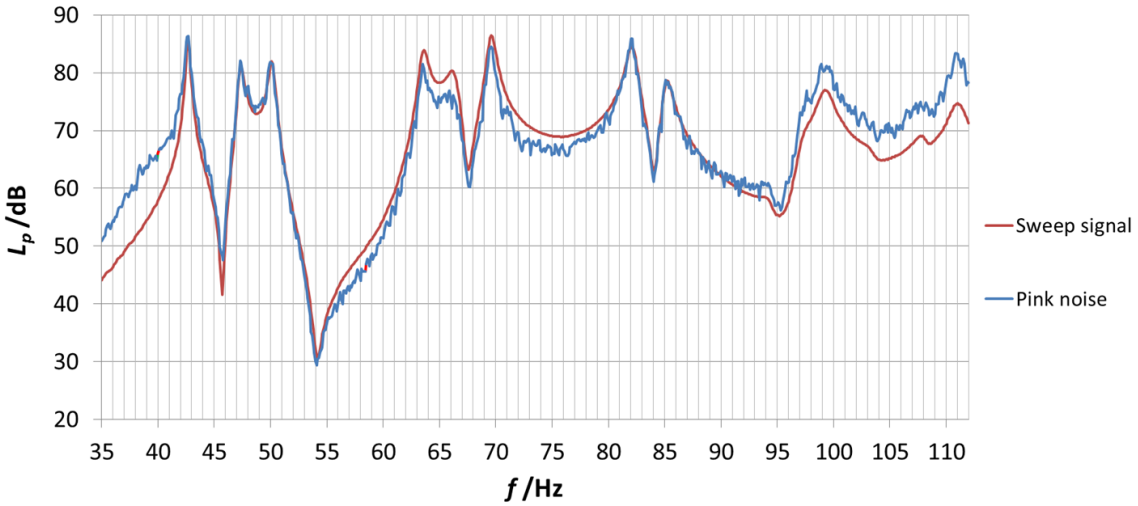

Figure 4: Modal spectra generated with a pink noise and a sweep signal.

Table 3: Summary of modal reverberation times evaluated with pink noise and sweep signal and comparison of residual standard deviations of Lorentzian best fits.

	Pink noise		*Sweep*	
f_n / Hz	T_n / s	s_{res} / dB	T_n / s	s_{res} / dB
42.5	5.83	0.14	7.46	0.18
47.5	6.34	0.19	4.38	0.16
50.0	4.06	0.24	3.96	0.16
63.5	4.26	0.26	2.50	0.13
66.0	1.49	0.21	2.19	0.11
69.5	4.12	0.22	2.99	0.08
82.0	4.71	0.22	2.42	0.13
85.5	2.26	0.26	2.29	0.10
99.25	1.61	0.20	1.31	0.06

3.3 Comparison between standard approach and modal approach

In order to get a comparison between modal and standard approaches, spatial measurements (as indicated in ISO 3382) were performed. On the basis of the previous conclusions, direct measurements were performed with 75 Hz anti-resonant sine wave as source signal, while indirect measurements were performed with a sweep signal (30-200 Hz with a linear increase of 10 s). Microphones were placed at 7 room corners (one corner is occupied by the loudspeaker) as positions of maximum modal excitation in that room [17]. Three inner positions were also tested but, since some modes were suppressed due to the presence of nodes, such positions were discarded. Comparison between standard and modal reverberation times depicted in Fig. 5 shows that standard procedure entails inaccurate (differences in the range between 1.1 s and 3.6 s) and imprecise values (compare standard deviation error bars between modal reverberation times and third octave bands reverberation times) compared to modal reverberation times. Direct and indirect methods, instead, show a good agreement since mean values are consistent. This means not only that the methodology contained in the ISO 3382 has been adapted for reverberation time measurements at low frequencies, but the relation between the modal reverberation time and the half bandwidth of resonant peaks in Eq. (4) has been experimentally proved. Besides, it is shown how modal reverberation times de-

crease with frequency, as also confirmed by theory: first axial modes are more energetic and their decay time is longer [16].

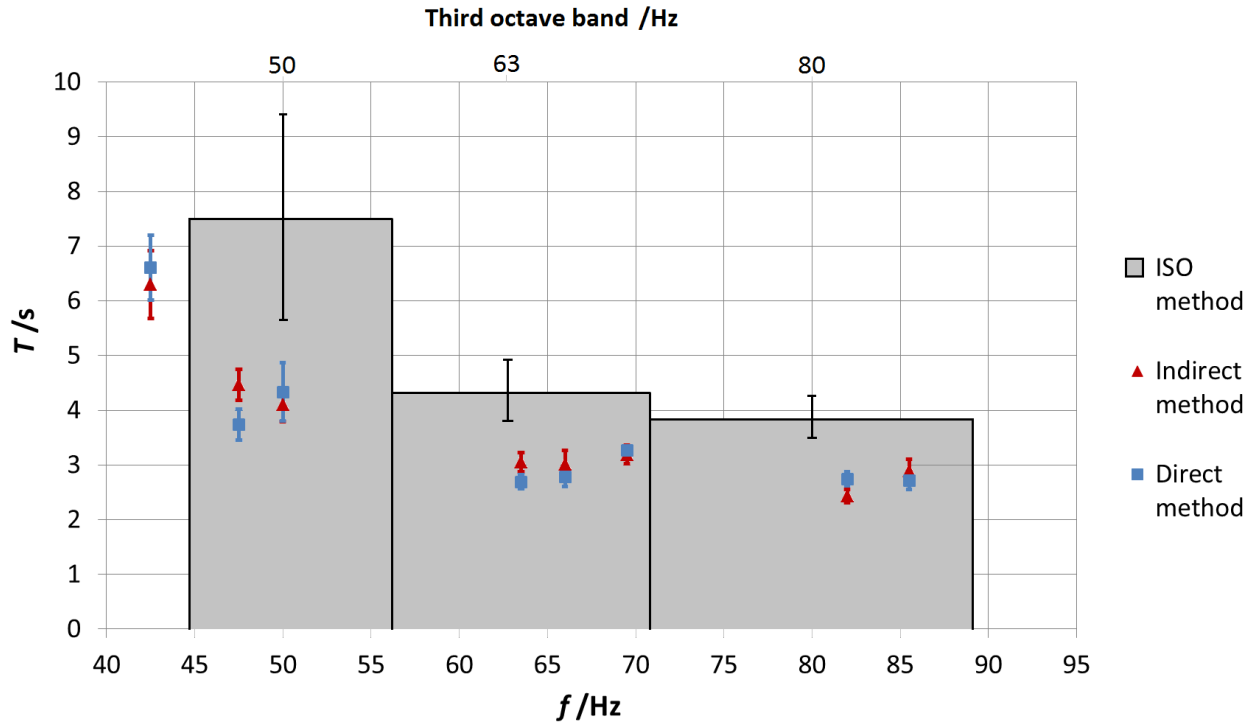

Figure 5: Direct and indirect modal reverberation times compared to ISO standard measurements in the empty test room. Error bars correspond to experimental standard deviations.

4. Conclusions

In non-diffuse sound field conditions, the non-linearity of sound pressure level decays in one-third octave bands suggest to focus just on resonant frequencies, as the most influential parameters of acoustic field and main cause of annoyance on humans in terms of quality of listening. Following this approach the modal reverberation time is introduced. In particular two measurement methods were investigated in an empty rectangular room: the direct method and the indirect method. For the first one, starting from the interrupted noise procedure stated in ISO 3382-2:2008, different source signals were compared: pink noise and anti-resonant sine waves. The last ones show cleaner and clearer decays. Indirect method, whereas, requires measurement of half bandwidths of modes, mathematically related to modal reverberation time. The source sweep signal is preferable with respect to pink noise as spectra are smoother and half bandwidth calculations are even more precise.

Comparison between direct and indirect methods for modal reverberation time measurement shows a good agreement as results are consistent and comparable. This is the first experimental validation of the relation between half bandwidth of resonant frequencies and modal reverberation time. Furthermore, comparing means and standard deviations of modal reverberation times with standard reverberation times in third octave bands, large discrepancies and higher dispersion of standard values are shown. This is a confirmation of the inadequacy of standard procedure to get accurate and precise values in non-diffuse sound fields.

Further evaluations in order to assess the influence of furniture in condition of damped modal field are deepened in the related paper [1]. Also in this case, it has been shown that the modal approach provides better results compared to standard ones in terms of accuracy and precision.

Such work, together with a recent one about the calculation of normal modes decay rates at low frequencies in rectangular and nearly rectangular rooms [18], allows to develop particular solutions

for low frequencies measurements in building acoustics and for room acoustic treatment, to guarantee good quality of listening in spaces like recording studios or small concert halls.

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