THE IMPROVED SYSTEM FOR ELECTRO-ULTRASONIC NONLINEAR SPECTROSCOPY

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Abstract*:*

The improved method of the new principle of non-destructive testing of conducting solids is presented [8]. This method is based on ultrasonic phonons interaction with electrons in the nonlinear region caused by defect. Tested sample is excited by harmonic electrical signal with frequency f_E and ultrasonic wave with frequency f_U. New harmonic signal with frequency f_i is created on the defect caused nonlinearity. The frequency f_i is given by the superposition or subtraction of exciting frequencies f_E and f_U. The advantage of this method consists in detection of electrical signal with frequency different from frequencies of excitation signals. Therefore the new variants of circuitry are designed and used for experimental verification. First of all the equivalent dynamic range and final sensitivity is improved by use of linear filters. They reduce the level of exciting signals and decrease theirs noise component. The theoretical sensitivity of this method and its limitation by parasitic effect is discussed and parasitic effects minimisation is confirmed by practical experiments.

Keywords: non-linear spectroscopy, ultrasonic, cracks, metal body, electrical excitation

1. INTRODUCTION

We present improved principle of non-destructive testing of conducting solids ([1], [2] etc.). This method should bring new possibilities as

a) increasing of sensitivity (reducing of minimum dimension of defect in relation to ultrasonic wave length)
b) defectoscopy of bodies with more complicated forms
c) integral testing (without localization of defect and need lower time for experiment performance)

It is known that non-linear interaction of crack with ultrasonic wave propagation is sensitive indicator of material un-homogeneities caused by defects. The creation of new frequency components by non-linear effect can be relatively easy detected by the frequency spectral analysis.

On the other hand, efforts to realization and application of these new principles bring many practical problems. There are various types of parasitic signal influences that essentially decline the theoretical sensitivity of this method [3]. This effect decreases practical sensitivity. The easiest method can be applied to samples with narrow band resonance properties where the crack induces unambiguous frequency shift of the corresponding resonance components in frequency spectrum [5, 6, 7].

Experimental verification of this method was performed on samples of thick film resistors and thick conducting films both without and with cracks prepared artificially [8]. Application of standard testing method for thick film resistors shown that the amplitude of intermodulation component $V_{E\text{-}U}$ increases approximately 6times, while the third harmonic voltage (THV) value changes for less than 5%. The application of new method where the amplitude of intermodulation component Ai is measured allows using lower stressing pulse energy to evaluate quality and reliability of thick film resistors.

2. BASIC PRINCIPLE OF ELECTRO-ULTRASONIC NONLINEAR SPECTROSCOPY

The principle of this method is graphically described in Fig. 1. A tested metal object is mechanically excited through ultrasonic transmitter by signal with frequency f_U. The electrical source V_E realizes the electrical excitation by conductive connection through load resistor R_L to tested subject. The nonlinear effect of crack causes the non-harmonic electrical current $I_{\Sigma E}$ and non-harmonic voltage $V_{\Sigma E}$ on connecting nodes of tested object. This voltage is amplified and filtered by low-pass and band-pass filter. By this processing we obtain the resultant signal with frequency f_E - f_U as information about defect in tested metal body.

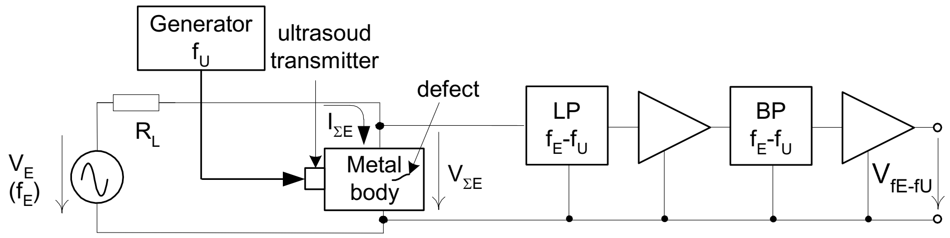

Fig. 1 Basic block diagram of the electro – ultrasonic spectroscopy

Fig. 2 shows up this principle in a frequency spectrum domain. It use the mixing principle, where the resultant non-harmonic voltage $V_{\Sigma E}$ contains spectral components

$$f_i = \left| \pm nf_E \pm mf_U \right|_{n,m=0,1,2....} . \quad (1)$$

The most important component has frequency f_i= f_E - f_U. It is shown how to obtain this component in Fig. 2. A spectrum of the exciting ultrasonic and electrical signals is expressed in Fig. 2a and 2b. The main part of resultant spectrum is shown in Fig. 2c, where the higher components are not important and they are not displayed. As we can see, the resultant component f_i is very small in comparison with electrical exciting signals and direct processing of this signal is not possible for high dynamic range of all signal (>100 dB).

The amplitude of the intermodulation component with frequency f_i depends on electrical and ultrasonic excitation. Therefore only extremely high ultrasonic excitation gives relative higher value of the signal on frequency f_i= f_E - f_U. On the other hand, a realisation of the extremely high ultrasonic excitation is very problematic for more reasons. Therefore we use the way with lowering of the dynamic range by electrical frequency filters because we have good experience with this technique in area of testing of electrical contacts [9].

As is shown in Fig. 2d and 2e, the use of low-pass filter with suitable cut-off frequency suppresses the magnitudes of exciting frequency components. The dynamic range of resultant signal is then acceptable for signal processing. In this case the low-pass filter has to be realised as ultra-linear for linear processing of the signal with high dynamic range.

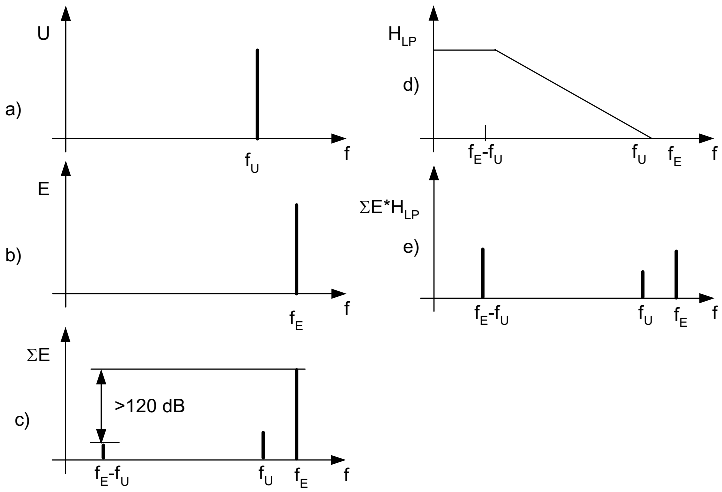

Fig. 2. Frequency spectrum of signals used by the parametric electro - ultrasonic spectroscopy: a) ultrasonic signal, b) electrical signal, c) resultant signal, d) frequency response of LP filter, d) filtered resultant signal with the lowered dynamic range

Now we can discuss a theoretical sensitivity of this principle. It is evident that changes of electrical resistance caused by ultrasonic excitation are very small due to a small change of resistance in the crack, which is electrically shorted by a surrounding conductive material with linear properties. Therefore it is necessary to survey the basic sensitivity of this method and optimize the signal to noise ratio. We can consider that relative change of resistance corresponds to ratio of value of differential component and value of exciting voltage on the load resistor R_L. Regarding to next signal processing, the basic limiting factor is $1/f$ noise of load resistor and preamplifier.

Thevenin's model of the measured signal source has an internal resistance R_i , which we can expressed as parallel combination of resistance R_M of tested metal body and load resistance R_L. Because the R_L have to be higher than R_M (for current limiting) the R_M value determines R_i. We can consider value in range 0.01 – 1 Ω. A thermal noise of this resistance is much lower than noise of low noise preamplifier. Therefore the preamplifier voltage noise V_n determines the basic sensitivity. We have to consider his equivalent voltage noise, because the equivalent current noise can be omitted for low value of R_i. It can be expressed as

$$V_n = V_{ne} \sqrt{B} \quad , \qquad (2)$$

where the V_{ne} is the voltage spectral density of preamplifier and B is noise pass-band frequency. It is evident that resultant noise can be essentially limited by reducing of B value. If we consider realisable pass-band frequency 1 kHz and voltage spectral density of low noise preamplifier U_{ne}= 1 nV/√Hz, we obtain equivalent noise

$$V_n = 1.10^{-9} \sqrt{1000} = 33nV \, . \qquad (2)$$

If we consider the exciting current I_E =1A (it is possible to increase up to 10 A), the sum voltage $V_{\Sigma E}$ will be approximately 0.1 V. Therefore the detectable relative value of the resistance change can be expressed as

$$\Delta R / R = 3.10^{-8} / 0{,}1 = 3.10^{-7} \, . \qquad (3)$$

Regarding to high difference of noise resistance of source and preamplifier (approx. 100 – 1000), it is possible to increase the sensitivity 10 times – 100 times by use of matching transformer. By this way, we can consider maximum basic sensitivity approximately 140-180 dB.

3. LIMITATION OF SENSITIVITY BY PARASITIC EFFECTS

The above calculated theoretical sensitivity (up to 180 dB) is practically limited by many parasitic effects. We can consider discussing following effects:

- thermal background noise of preamplifier
- rejection of external noise (50 Hz etc…)
- noise of electrical excitation signal
- rejection of exciting signals
- nonlinear property of electrical contacts
- parasitic nonlinearity of electrical exciting circuit
- parasitic nonlinearity of low-pass filter

The first group of effects relates with basic background noise in the measured frequency area as it was discussed above. It is caused not only by the voltage noise of preamplifier. A minimum of the noise spectral voltage density of preamplifiers is about 1 nV/√Hz and it cannot be fundamentally reduced. On the other hand the spectral density of an external noise in measured frequency area can be higher then preamplifier thermal noise. Therefore it is necessary to apply the good known thesis about grounding, dividing of power sources and circuits for electrical and ultrasonic exciting, shielding etc.

Further problem is connected with a noise of the power generator of electrical exciting. It offers except of the exciting harmonic signal with frequency f_E also the noise signal in wide frequency area with dynamic range about 60-100 dB. The noise components with frequencies about f_E - f_U are transmitted directly through the LP filter as measured signal and raise the background noise. It is shown in Fig. 3 a, b. Therefore it is necessary to suppress this parasitic noise by HP filter (Fig. 3.c) and reduce the background noise (Fig. 3.d).

On the other hand, the rising of measured signal up the noise floor can be realized by rising of the electrical signal by a transformer because the resistance of tested object is much more lower then output resistance of an amplifier and the transformer can rice the exciting electrical current. This solution improves the signal/noise ratio but the dynamic range of measured signal didn't change. The circuitry for this case is in Fig. 4.

Very important task of signal processing consists in suppression of exciting signals before amplifying and other signal processing with limited dynamic range (see Fig. 2d,e). This suppression has to be sufficient (40-80 dB) and it has to be realized by linear passive low-pass filters. The simplest solution uses the RC filters, but it has a low suppression. Therefore the LC filers have to be used. On the other hand the requirement of pure linearity demands a use of linear inductors without ferromagnetic core and special linear capacitors; because some types of capacitors have substantial nonlinearity (< 80 dB). Other special problems of this one will be discussed further.

Last group of unwished effect is connected with nonlinear parasitic properties. One problem of nonlinear elements of low-pass filter was reminded above. It is also necessary to discuss the electrical contacts on tested object as a further parasitic nonlinear source. In the case of mechanical connecting, they are also sensitive to ultrasonic exciting similarly as asked crack. Minimization of this effect has more possibilities as soldering, mechanical connecting with strongly olted down copper contact. A pulse ultrasonic exciting makes possible the time elimination of this parasitic result signal. Effective way of rejecting of this parasitic ultrasonic modulation is able by four-point connection as it is shown in Fig. 5a.

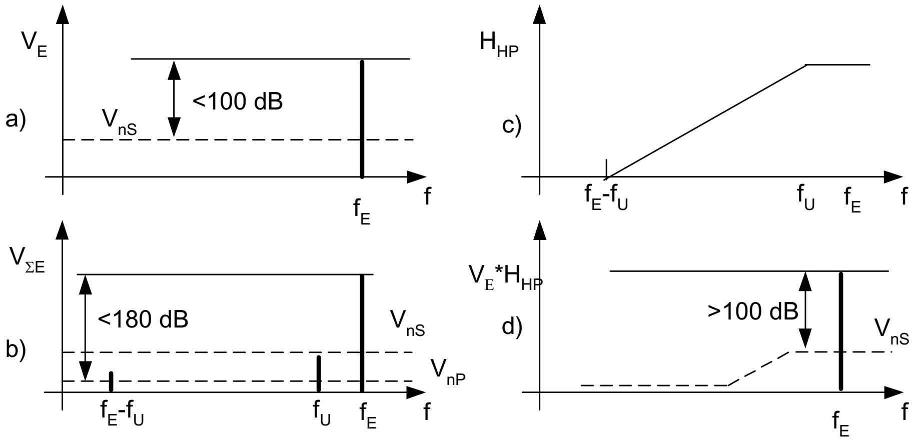

Fig. 3. Spectrum of signals and noise relations of the electrical source V_E: a) electrical exciting signal and noise, b) relations in the result signal in tested metal body, c) a frequency response of AC source HP filter, d) the exciting signal and noise after filtration

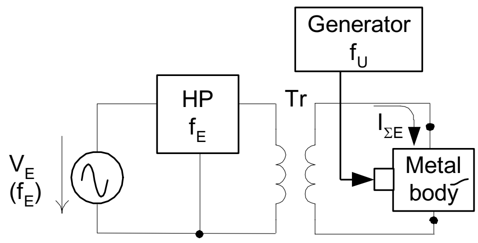

Fig. 4. Possibility of improving of the electrical exciting circuit (in comparison with Fig. 1)

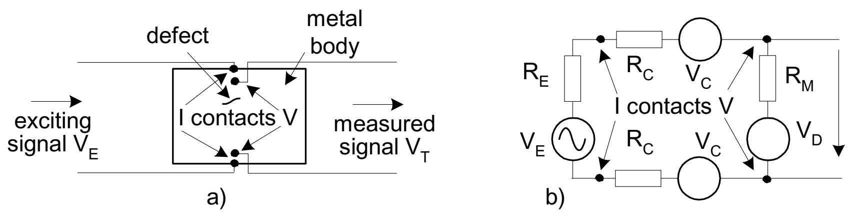

Fig. 5. Testing variant with current and voltage contacts and electrical substitution diagram: a) realization, b) electrical substitution diagram

This principle is well known from electrical testing of low resistive elements as so-called 4-pint connection with current and voltage contacts, where the main current flow trough the current contacts whereas the voltage contact are not loaded by current. It is described by electrical substitution diagram in Fig. 5 b. The exciting source is expressed by source V_E with internal resistance R_L (c. 1 Ω). The parasitic signal of contacts expresses the sources V_C. Their internal resistance is similarly the same as internal resistance of measured metal body (c. 0.001-0.1Ω). It is very important to calculate transfer coefficients k_{VD} and k_{VC} of useful signal V_D (caused by defect) and parasitic signal of contacts V_C to measured signal V_T. The transfer coefficient k_{VD} of useful signal V_D can be expressed as voltage divider

$$k_{VD} = \frac{R_C + R_E}{R_C + R_E + R_M} \rightarrow 1. \quad (4)$$

This value is nearly 1 because value of $R_E >> R_M$. On the other hand, the transfer coefficient k_{VC} of parasitic signal V_C is

$$k_{VC} = \frac{R_M}{R_C + R_E + R_M} << 1. \quad (5)$$

The rejection of parasitic signal V_C in comparison with useful signal V_D can be expressed as ratio

$$\frac{k_{VD}}{k_{VC}} = \frac{R_C + R_E}{R_M} \quad (6)$$

and the practical value of rejection is approximately 100-1000.

Similarly as the parasitic nonlinearity of tested object, it is necessary to discuss a parasitic nonlinearity of all electrical exciting circuit because it can also mix exciting electrical signal and transformed ultrasonic signal as electrical signal. Therefore the transformers without ferromagnetic cores and linear load resistor with higher resistance have to be used.

4. ADVANCED EPERIMENTAL TESTING SYSTEM

Pursuant to above discussed problems and actual experiences [8] we tried to improve basic testing apparatus. It is necessary to remark that there are more possibilities for connecting. For example we leave the way of current sensing of testing signal [8] and we return to voltage connecting as it is used and described above. In comparison with discussed connection of electrical excitation circuit (Fig. 4) we didn't use an exciting transformer because the direct electrical excitation was sufficient. On the other hand we use a transformer in the signal processing way as it is shown in Fig. 6. Instead of filtration of result frequency component with frequency f_E-f_U, we used the 16/bit AD conversion and FFT displaying of all result spectrum, because it brings more information for research work.

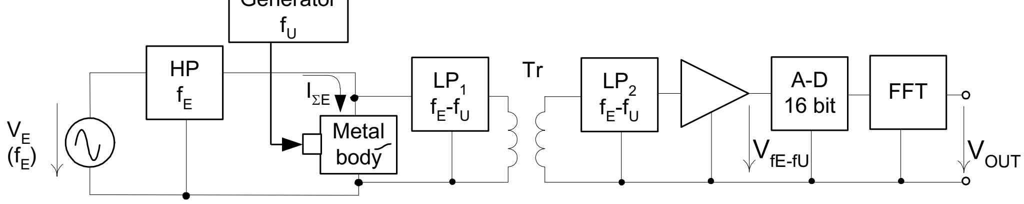

Fig. 6 Improved system of nonlinear ultrasonic-electrical spectroscopy

The use of transformer brings three advantageous. First, the transformer matches the low resistance R_M to higher input impedance of preamplifier and it raises the result voltage.

Second, it transforms the impedance level for simpler realisation of second part of low-pas filter (LP_2) that realises the main selectivity. Further advantage consists in separation of excitation ground and signal processing ground. It minimizes a leakage of parasitic external noises through the ground loops.

5. EPERIMENTAL RESULTS

This method was verified at set of six samples of dural flat beams with hole for pins, see Fig. 7. Four samples were periodically oppressed to obtain small cracks around the whole. Next two samples weren't oppressed as reference.

Fig. 7 The sample of a dural flat beam

The testing system was set to use ultrasonic frequency f_U = 30.9 KHz (for resonance frequency of power piezoelectric transmitter). The electrical excitation was used with frequency f_E = 35.0 kHz. Than we obtained the result frequency

$$f_E - f_U = 35.0 - 30.9 = 3.9 \text{ kHz}. \quad (7)$$

Therefore the LP filter with cut-off frequency 4 kHz was used.

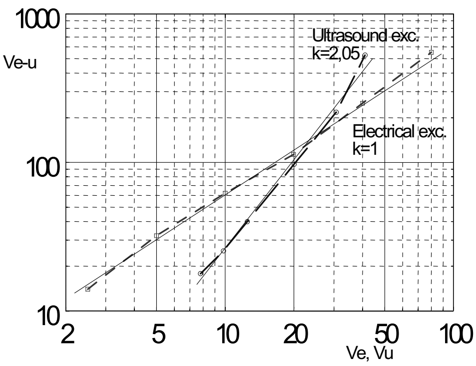

Fig. 8 Intermodulation component $V_{E\text{-}U}$ vs. excitation signals V_E and V_U

First, we started with experimental verification how the resultant intermodulation component $V_{E\text{-}U}$ depends on excitation signals V_E and V_U. As is shown in Fig. 8, this experiment confirms the linear dependency of intermodulation component $V_{E\text{-}U}$ on electrical excitation V_E and the square dependency on ultrasonic signal V_U. It is necessary to consider the values and units as relative because the actual values depend on setting of amplifiers and other transmitting elements. Nevertheless it doesn't chance the form of theses dependences.

In the next step we measured spectrums for all six samples. The typical result spectrums with various values of intermodulation components $V_{E\text{-}U}$ are shown in Fig. 9. If we consider the gain 40 dB of amplifier and pass-band of FFT filters, the voltage spectrum density corresponds to this spectrum lowered for 48 dB. Then the background noise for frequencies up 10 kHz corresponds to the voltage noise of the preamplifier. On the other hand, the noise background for pass/band of LP1 and LP2 filters is 10-times higher (20 dB). It has to be caused by noise of electrical excitation as it was discussed above.

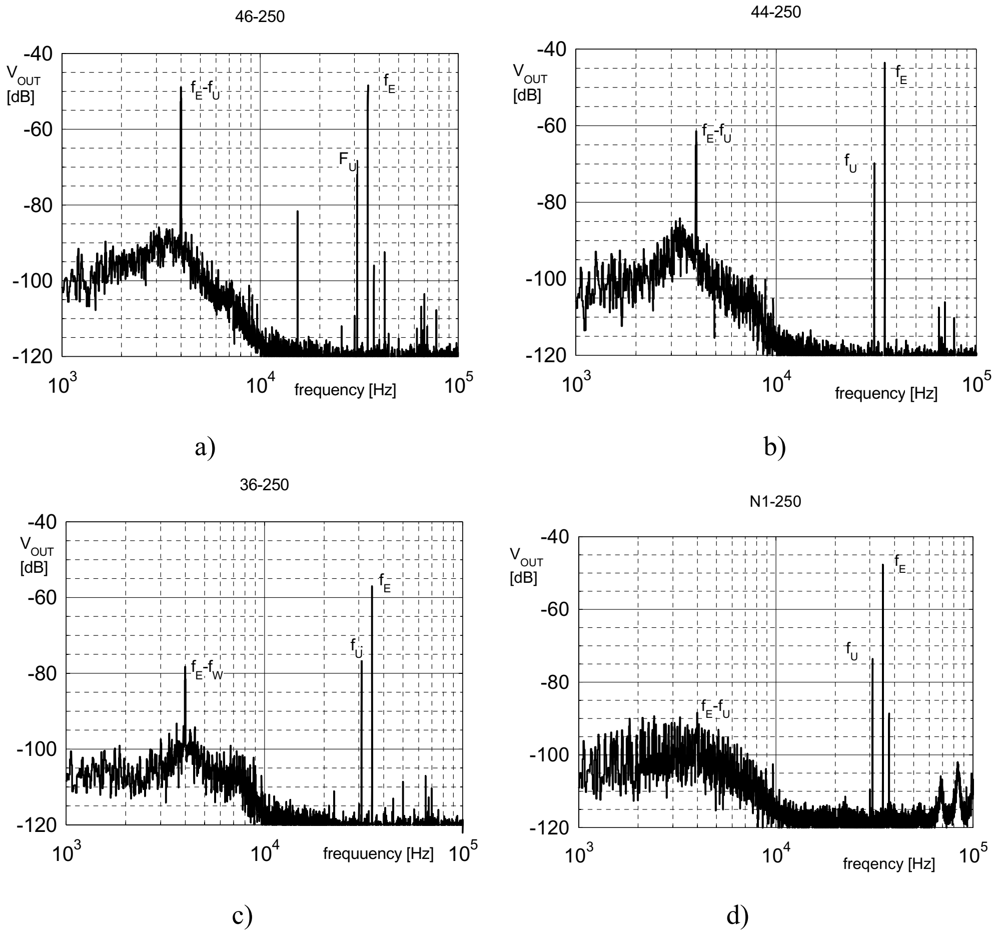

Fig. 9. Spectrum of measured signal for various samples: a-c) samples with cracks, sample without cracks.

Further we can see the well detectable intermodulation components V_{E-U} for samples with the crack. The Table 1 shows comparison of results for all samples. Here the component V_{E-U} was expressed as difference in comparison with electrical excitation as V_E - V_{E-U} in dB.

Tab. 1

No. of sample	46	44	36	31	N1	N2
l of crack [mm]	3.1	3	4.5	2.7	-	-
Δ [dB]	1	11	21	31	41	38

5. CONCLUSIONS

This paper discuss possibility of improve of the new principle of non-destructive testing of cracks for bodies with electrical conductivity [8] as a special variant of ultrasonic non-linear wave modulation spectroscopy. The main advantage of this method consists in electrical sensing of resultant intermodulation component $V_{E\text{-}U}$ as a product of the crack's mixing effect, whereas the mechanical sensing by piezoelectric sensors has more parasitic effects.

On the other hand there are also some parasitic effects which lower the sensitivity of this new method. Therefore we lowered the background noise of result signal by rejection of external noise and noise of the electrical excitation. Further we lowered the dynamic range of processed signal before electronic processing by special low-pass LC filters with high linearity and linear transformer. By this way the parasitic nonlinearity of the electronic processing was minimised. We solve also other parasitic nonlinearity of current electrical contacts and of all excited circuit.

Practical experiments confirm a usability of this principle and possibility of minimisation of parasitic effects. On the other hand the correlation between the cracks dimensions and measured $V_{E\text{-}U}$ values is not sufficient as show Table 1. It is caused among others by influence of standing waves for CW mode, non-stability of the value of result ultrasonic power etc.

Acknowledgement

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