

1 *Article*

2 **Pressure detrending in Harmonic Pulse Test** 3 **interpretation: when, why and how**

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10 **Abstract:** In reservoir engineering, one of the main sources of information for the characterization
11 of reservoir and well parameters is well testing. Among the unconventional well testing
12 methodologies, Harmonic Well Testing (HPT) is appealing from an economic standpoint because it
13 could provide well performance and reservoir behavior monitoring without having to interrupt
14 field production. Recorded pressure analysis is performed in the frequency domain by adopting a
15 derivative approach similar to conventional well testing. To this end, pressure and rate data must
16 be decomposed into harmonic components. Test interpretability can be significantly improved if
17 pressure data are detrended prior to interpretation, filtering out non periodic events such as
18 discontinuous production from neighboring wells and flow regime variations which did not respect
19 the designed test periodicity. Therefore, detrending offers the possibility of overcoming the
20 limitation of HPT applicability due to the difficulty of imposing a regularly pulsing rate for the
21 whole test duration (typically lasting several days). This makes HPT attractive for well performance
22 monitoring, especially in gas storage fields. In this paper, the application of different detrending
23 methodologies to synthetic HPT pressure data generated in different reservoir and operational
24 scenarios is presented and discussed. Moreover, a real case application is also presented.

25 **Keywords:** well testing, detrending, harmonic pulse testing, well performance monitoring,
26 underground gas storage

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28 **1. Introduction**

29 Broadly speaking well testing provides pressure measurements which are mainly used for
30 determining reservoir-rock properties and producing-formation limits and as such it is considered
31 an effective method of reservoir analysis. Conventional well tests have been used by reservoir
32 engineers to evaluate well and reservoir performance for decades ([1–5]); by doing they aim at
33 reducing uncertainty as much as possible in addition to trying to understand that part which cannot
34 be reduced. Over the last years, work has focused on developing unconventional or, perhaps more
35 accurately, complementary well test methodologies that are both less expensive and more
36 environmentally friendly procedures ([6–14]).

37 These complementary well test methodologies can prove reliable alternatives to obtaining a
38 reasonable amount of information when conventional well testing cannot be applied. Among the
39 complementary well testing methodologies, Harmonic Pulse Testing (HPT) is appealing from an
40 economic standpoint as it can provide well performance and reservoir monitoring without having to
41 interrupt field production. In HPT a pulsed signal is superimposed to the background pressure trend;
42 thus no interruption of well and reservoir production is required before and during the test.

43 Simple Pulse testing as a methodology for reservoir properties characterization dates back to
44 1966 when it was first proposed by Johnson et al. ([15]). Since then, theoretical developments have
45 led to the current characteristic of periodicity of the original test procedure which allows the

46 application of interpretation methodology in the frequency domain ([16–33]). Thus, a harmonic test
47 is that in which the injection or production rate is varied in a periodic way. These rates can be imposed
48 after a long shut in of the tested well, like in conventional well testing, or they can be superposed to
49 ongoing production and without interrupting the production activities from other wells, hence the
50 economic benefit of the methodology. However, HPT does show a limitation in terms of the
51 investigation distance, which is shorter for the same test duration as compared to that of a
52 conventional well test. Additionally, reliable test interpretation means regular sampling of the
53 pressure data and reasonable periodicity of the imposed rate signal. Despite the aforementioned,
54 HPT methodology and interpretation does not require the initial static pressure nor the previous
55 production history of the well which in turn are considerable advantages ([33]).

56 Pressure and rate signals recorded during HPT are first analyzed in the frequency domain with
57 proper methodologies, mainly based on Fourier Analysis, to then be interpreted by adopting a
58 derivative approach similar to that of a conventional well test [33]. Pressure data should be
59 adequately pre-processed with detrending methodologies to separate pure periodic components of
60 the signal from non-periodic components; in this way the information obtained from HPT
61 interpretation can be maximized. First transient magnitude, discontinuous production from
62 neighboring wells, flow regime variations, etc. produce a significant non-periodic component in the
63 pressure response which might strongly affect the periodicity of the pressure signal and hence the
64 reliability of test interpretation.

65 To filter out non-periodic components different detrending approaches have been suggested in
66 the literature: for instance, Hollaender ([20]) adopted a polynomial reconstruction of the aperiodic
67 depletion trend; and more recently detrending approaches based on a heuristic reconstruction of a
68 constant depletion have been presented ([25], [34]).

69 In the present paper, four detrending methodologies (method 0, method 1, method 2 and
70 method 3 hereinafter) are considered and discussed. Method 0 is the simple linear detrending.
71 Method 1 is an interesting and efficient heuristic algorithm proposed by Ahn and Horne ([35]).
72 Methods 2 and 3 ([34]) are heuristic algorithms developed by the authors in steps, initially with the
73 aim of overcoming some limitations of the Ahn and Horne algorithm, and subsequently to extend
74 the approach to any possible scenario as well as to better characterize the periodic and the non-
75 periodic components.

76 The four detrending algorithms were applied to several synthetic cases representative of
77 possible scenarios and to a real gas storage case. The resulting detrended harmonic signals were
78 analyzed in the frequency domain adopting the approach presented by Fokker et al. ([33]) and
79 compared in terms of quality of the harmonic components derivative and interpretation results.

80 Furthermore, the four detrending algorithms were applied to a real case in which temporarily
81 test interruptions due to operational constraints negatively affected pressure response periodicity.

82 2. Results

83 In order to validate and compare the presented detrending methodologies, several synthetic
84 cases were generated. Each case represents a different scenario characterized by both reservoir
85 behavior and production operations or events that can potentially affect the test. From a reservoir
86 behavior viewpoint, three main scenarios were considered:

- 87 • Simple homogeneous system
- 88 • Presence of one boundary within the investigated area of the test
- 89 • Closed system with high depletion

90 From a production operations or events viewpoint, several possible situations were taken into
91 account:

- 92 • Interfering well produced with constant rate
- 93 • Interfering well production with rate variation longer than the oscillation period
- 94 • Interfering well production with rate variation shorter than the oscillation period
- 95 • Well shut in prior to test

- 96 • Complex historical productions (preceding the test) not available for the interpretation. Only
97 the value of the last rate before the test is known.

98 In all scenarios, the use of a detrending algorithm proved valuable to improve data quality and
99 hence test interpretation. A selection of the scenarios is described in detail in the following sections
100 3.1 - 3.4 of this paper. The common data adopted for the generation of synthetic cases are summarized
101 in Tab. 1; pressure and rate data are generated with a constant sampling interval of 10 s. The rates
102 adopted to impose the harmonic oscillation will be indicated as q_1 and q_2 , whereas q_0 refers to the last
103 historical rate prior to the HPT. The rate is obviously null when initial static conditions are simulated
104 at the beginning of the test.

105 In addition, a real gas well HPT was analyzed; the test was interrupted twice for several hours
106 because of operational constraints, thus inducing two considerable irregularities in the pressure
107 periodical trend.

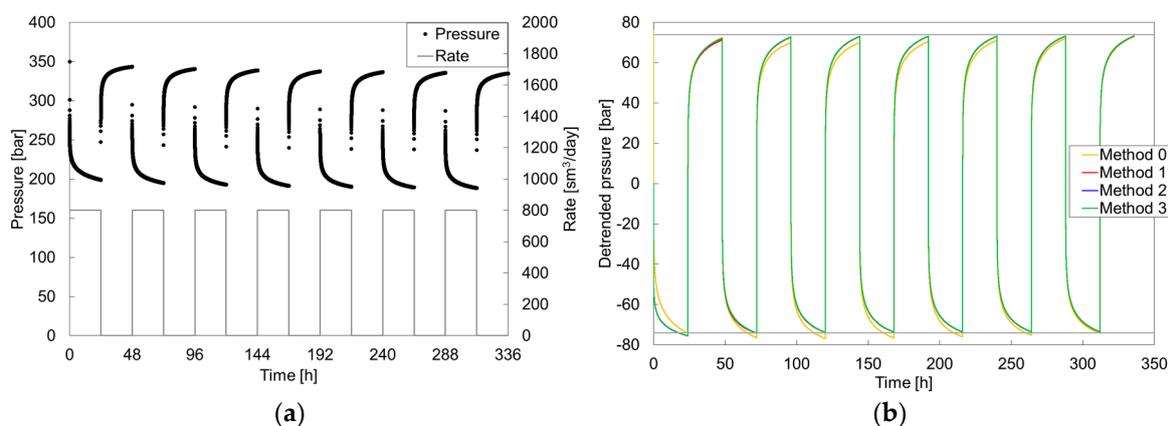
108 **Tab. 1:** Common data adopted for synthetic case generation.

Parameters	Values
Permeability	100 mD
Porosity	0.2
Net pay	10 m
Initial pressure	300 bar
Total compressibility	1.646E-4 bar ⁻¹
Oil volume factor	1.3
Oil viscosity	1 cP
Well radius	0.1 m
Wellbore storage	1 e-8 Pa/m
Skin	0

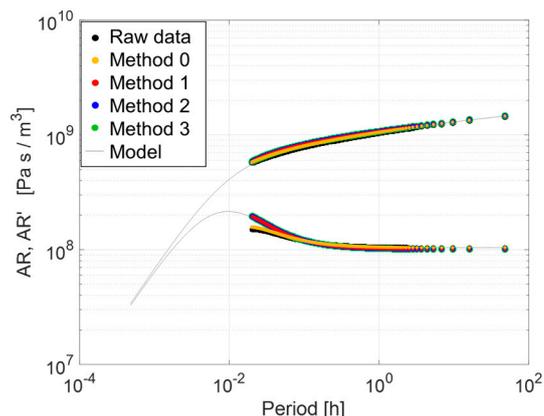
109 2.1 Synthetic case 1: ideal condition

110 The first selected case presents ideal conditions to preserve the periodic trend of pressure
111 response. Production starts from the initial static conditions. The test consists of seven oscillating
112 cycles in which constant production of $q_1=800$ m³/day is alternated with shut in of $q_2=0$ m³/day every
113 24 hours (**Fig. 1a**).

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115 **Fig. 1:** Synthetic case 1: (a) imposed rate and pressure response; (b) detrended pressure data.



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Fig. 2: Derivative in the frequency domain.

118 Neither well interference nor significant overall pressure decline are imposed. Moreover, the
 119 influence of the initial transient is very limited because $q_2 = q_0$. Therefore, the derivative of raw data
 120 is interpretable only because high frequency harmonics ($T < 0.1h$) are affected (**Fig. 2**).

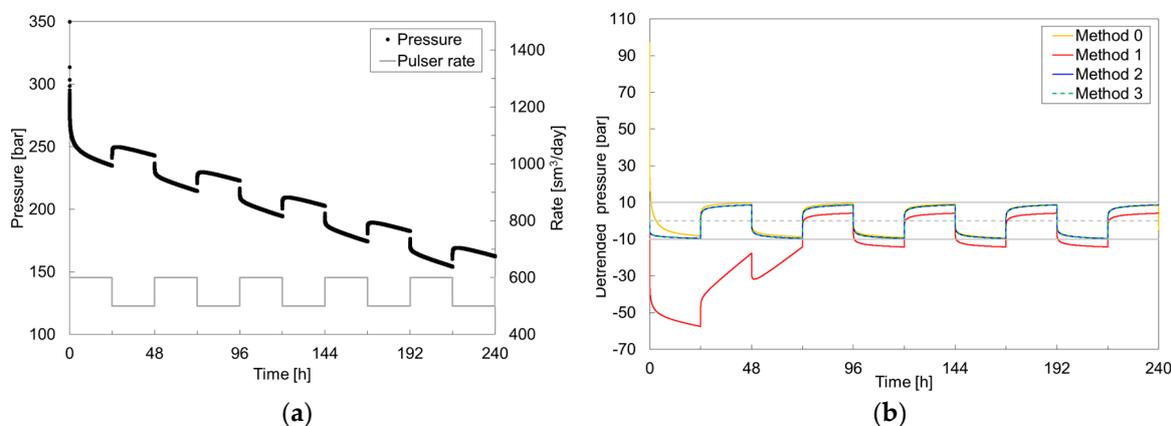
121 Linear detrending is not well suited to remove the initial transient effect (**Fig. 1b**). On the
 122 contrary, the adoption of any of the heuristic detrending strategies presented in section 4 improves
 123 the pressure data (**Fig. 1b**) and, in turn, the derivative for high frequency components (**Fig. 2**). Notice
 124 that in this case derivatives obtained from detrended data with methods 1, 2 and 3 perfectly overlap.

125 2.2 Synthetic case 2: depletion

126 In the second case, strong reservoir depletion is simulated by considering a closed reservoir of
 127 1000 m \times 1000 m with the pulser at the center and introducing a second well (well 1) at a distance of
 128 150 m from the pulser. The additional well is produced with a constant rate of 2000 m³/day.

129 The production from the pulser and from well 1 starts simultaneously and from the initial static
 130 conditions. The test is made up of five oscillating cycles in which rates are alternated every 24 hours
 131 between $q_1 = 600$ m³/day and $q_2 = 500$ m³/day (**Fig. 3a**).

132 Two effects mask the periodic trend under the described pressure profile: the depletion trend
 133 and a pronounced initial transient. In fact, being $q_0 \neq q_2$, the magnitude of the first pressure transient,
 134 corresponding to the first hemicycle (from 0 to $\frac{T}{2}$), is significantly higher than the following pressure
 135 oscillations; the more q_0 differs from q_2 , the more the initial transient masks the periodic trend in
 136 pressure data.
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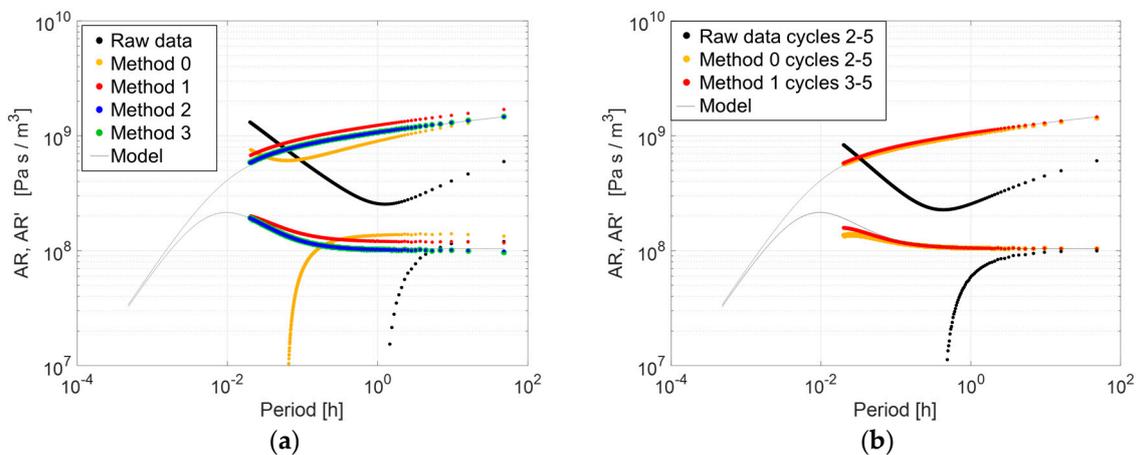
Fig. 3: Synthetic case 2: (a) imposed rate and pressure response; (b) detrended pressure data.

139 All the detrending strategies presented in section 4 were applied; the obtained detrended
 140 pressures are compared in **Fig. 3b**. Moreover, results are compared on log-log plots in which the

141 amplitude ratio of harmonic components of the pressure and rate spectrums and their derivative
 142 (referred to as derivative hereinafter) with respect to the oscillation period are represented. The
 143 results obtained for raw data and for the pressure data processed with methods 0, 1, 2 and 3 are
 144 represented Fig. 4a.

145 The analysis of the log-log plot (Fig. 4a) shows that the derivative of the raw data and of method
 146 0 detrended pressure do not provide reliable interpretation for both high frequencies (low T values)
 147 and low frequencies (high T values). Significant errors in the estimation of the kh (underestimation
 148 of 25%) and of the skin ($S=-2.5$ instead of 0) are observed. The derivative of method 1 detrended
 149 pressure is affected, as expected, by the first transient and would induce an underestimation of kh of
 150 10% and a slightly incorrect evaluation of mechanical skin ($S=0.5$ instead of 0). However, both
 151 approaches are still applicable if the number of oscillating cycles is high enough (which is rarely the
 152 case in real applications) to allow removing the first cycle, which is strongly influenced by initial
 153 transient due to $q_0 \neq q_2$ (Fig. 4b). The removal of initial transient is anyhow not sufficient to analyze
 154 raw data because the linear trend still masks periodicity.

155 Method 2 and method 3 give very similar results (derivatives overlap), and provide an excellent
 156 match with the theoretical model.
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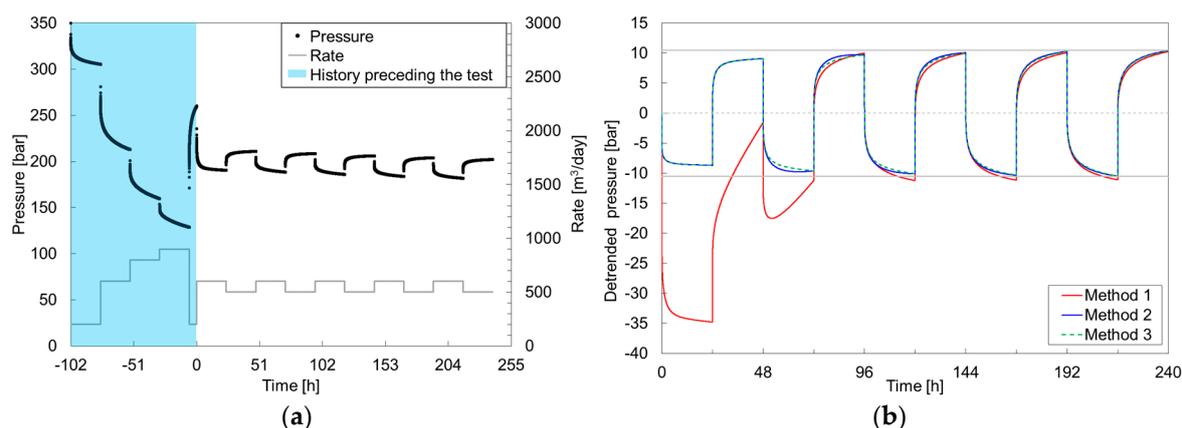
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159 **Fig. 4:** Derivative in the frequency domain: (a) all cycles; (b) cycles affected by transient excluded from
 160 the Fourier analysis.

161 2.3 Synthetic case 3: partially unknown pre-existing history

162 In the third selected case, a single no-flow boundary was defined at a distance of 30 m from the
 163 pulser. The well is produced with a changing rate before the test (see Fig. 5a); only the very last
 164 production rate ($q_0=200$ m³/day) preceding the test is needed for interpretation purposes. The test is
 165 made up of seven oscillating cycles in which rates are alternated every 24 hours between $q_1=600$
 166 m³/day and $q_2=500$ m³/day (see Fig. 5a).

167 The periodic trend is masked by the initial transient under this pressure profile.
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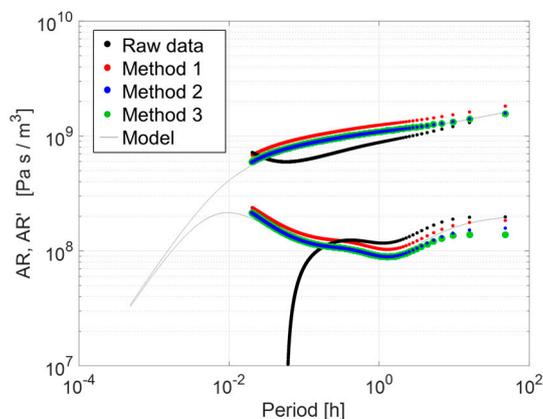


169 **Fig. 5:** Synthetic case 3: (a) imposed rate and pressure response; (b) detrended pressure data.

170 The heuristic detrending strategy presented in section 4 (method 1, method 2 and method 3) was
 171 applied and the obtained detrended pressures are compared in **Fig. 5b**. Moreover, results were
 172 compared against raw data in terms of derivative (Fig. 6).

173 The derivative of raw data induces an underestimation of the kh value of 20% and an incorrect
 174 evaluation of the mechanical skin ($S=-1.5$ instead of 0). The derivative of method 1 processed data
 175 induces an underestimation of kh of 8% and a slightly incorrect evaluation of mechanical skin ($S=-0.4$
 176 instead of 0). These errors are due to the incorrect detrending of the first cycle, which is strongly
 177 influenced by the initial transient due to $q_0 \neq q_2$. Methods 2 and 3 provide a reliable derivative
 178 (derivatives almost overlap), with a correct identification of the single boundary position.

179 It turns out that only the very last production rate preceding the test (q_0) has an impact.
 180 Consequently, detrending can be effective if the value of the last production rate prior to the test is
 181 known, even so when pre-existing production is complicated.



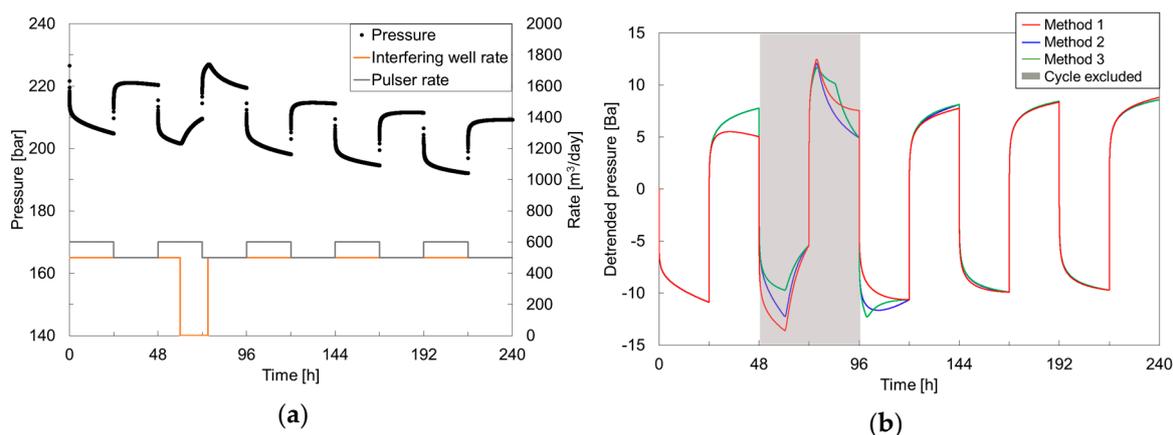
182 **Fig. 6:** Derivative in the frequency domain.

184 2.4 Synthetic case 4: sudden interference

185 In this case, an interfering well placed at 80m from the Pulsar is introduced. The well produces
 186 $500 \text{ m}^3/\text{day}$, but a sudden well shut in of 15 h occurs during the test. Both wells produced $500 \text{ m}^3/\text{day}$
 187 before the test ($q_0=500 \text{ m}^3/\text{day}$); the test is made up of five oscillating cycles in which rates are
 188 alternated every 24 hours between $q_1=600 \text{ m}^3/\text{day}$ and $q_2=500 \text{ m}^3/\text{day}$ (**Fig. 7a**).

189 Notice that, in this case, the pre-existing rate (q_0) is equal to the rate of the second oscillation
 190 hemicycle (q_2); therefore, no initial transient is observed and the first oscillation cycle is in line with
 191 the last two cycles. Conversely, the second cycle is highly affected by the rate change in the interfering
 192 well.

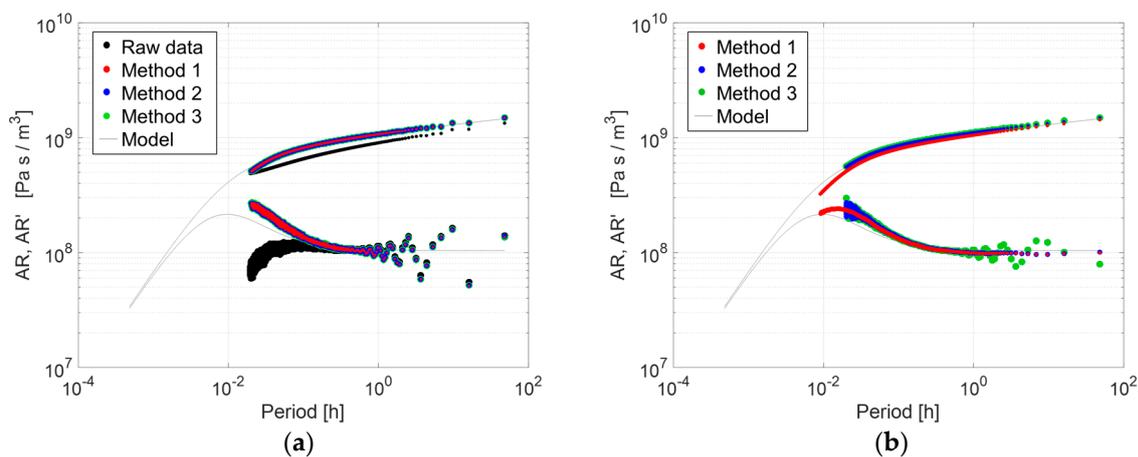
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194 **Fig. 7:** Synthetic case 4: (a) imposed rate and pressure response; (b) detrended pressure data.

195 The heuristic detrending strategies presented in section 4 (method 1, method 2 and method 3)
 196 were applied; the obtained detrended pressures are compared in **Fig. 7b**. In this case, the detrended
 197 pressure of method 1 and method 2 are similar whereas differ significantly from the detrended
 198 pressure of method 3. In fact, with method 2 (similarly to method 1) the irregularity due to the
 199 interfering well is marked and affects mainly the second cycle, while with method 3 the irregularity
 200 due to the interfering well is less marked because it is spread over two cycles. Results were compared
 201 against raw data in terms of derivative (**Fig. 8a**). It turns out that a rate change in an interfering well
 202 lasting less than the oscillation period (or hemicycle) has a strong impact on the derivative, which is
 203 highly noisy even at low frequency components; as a consequence the horizontal stabilization
 204 representing radial flow geometry in transient regime (Infinite Acting Radial Flow - IARF) is hardly
 205 detectable.

206 Successively, the most irregular oscillation period (cycle 2) was excluded from the analysis (**Fig.**
 207 **7b**) and the improvement in derivative interpretability is shown in **Fig. 8b**. Notice that method 3 is
 208 not well suited for detrending such scenario because it spreads the irregularity over more oscillating
 209 cycles, thus making the exclusion of the more affected cycle less effective.



210 **Fig. 8:** Derivative in the frequency domain: (a) all cycles; (b) cycle affected by interfering well
 211 excluded from the Fourier analysis.

212 2.5 Real case: temporary interruption of the test

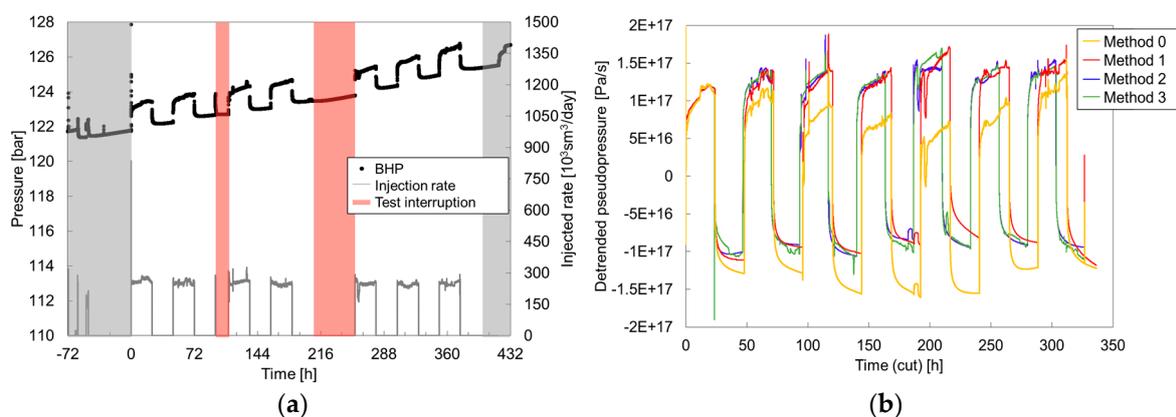
213 A gas storage well was tested during the injection campaign without interruption of the activities
 214 from the other wells of the field in Italy. The test design was a rate of 250000 m³/day for 24 hours
 215 alternated with well shut in of the same duration (**Fig. 9a**). Significant rate instability/fluctuations
 216 during the injection periods were due to operational and technical reasons. Downhole pressure data

217 was recorded every 10 s while rate data was recorded every 30 s; rate data was resampled according
 218 to pressure data. Due to operational issues after the first two cycles the test was temporarily
 219 interrupted (well was shut after 1.5 h of injection and remained shut for 13.5h) and was interrupted
 220 again for 47.5h (extended well shut in) after the following 1.5 cycle. Consequently, the overall test
 221 periodicity was seriously compromised and only few consecutive cycles were available. Except for the
 222 two test interruptions aforementioned, in most hemicycles rate changes were
 223 anticipated/postponed with respect to the design by a few to a maximum of 40 minutes. As a
 224 consequence, the raw test data does not meet the HPT interpretation methodology requirements of
 225 regular periodicity. In fact, when applying the Fourier analysis to the original data a scattered
 226 derivative is obtained (Fig. 10a), which is clearly not interpretable.

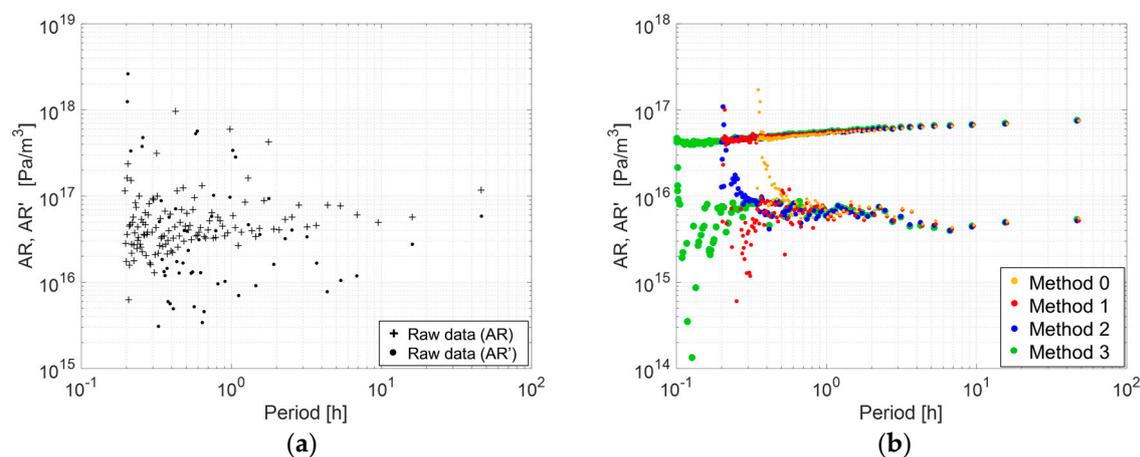
227 All the four detrending techniques described in section 4 were applied to pseudopressure data.
 228 Notice that method 0 and method 1 were suitable in this context because $q_2=q_0=0$, thus no initial
 229 transient was observed. However, detrending with method 0 was not completely successful because
 230 the slope of the linear trend changed after the second test interruption.

231 After detrending, the data portion related to the two test interruptions were removed; for
 232 method 2 and method 3, which gave more regular oscillations, a further regularization was applied
 233 by removing all the data portion related to hemicycle duration greater than the minimum one (23.34
 234 h). The detrended pseudopressure data obtained from each methodology is compared in **Error!**
 235 **Reference source not found.** Derivatives of detrended data are compared in Fig. 10b. All cases show
 236 great improvement and allow kh identification. Among the detrending strategies, method 3 allowed
 237 better extraction of early time information. The residual scattering observable on the derivatives for
 238 methods 2 and 3 is due to rate instabilities and for methods 0 and 1 to the residual flow period
 239 duration irregularity as well.

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241 **Fig. 9:** Real case: (a) imposed rate and pressure response; (b) detrended pseudopressure data with
 242 exclusion of main irregularities.



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Fig. 10: Derivative in the frequency domain: (a) raw data; (b) detrended data.

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3. Discussion

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The analyzed cases showed that only in the ideal case of negligible well interference – small overall pressure decline and negligible initial transient ($q_0 = q_2$) as in synthetic case 1 – the Fourier analysis of HPT raw pressure data is feasible. In fact, in the other considered scenarios (well interference, significant overall pressure decline, initial transient due to previous history) the derivative obtained from raw data analysis in the frequency domain was either not interpretable or the interpretation was not reliable. In such scenarios the use of a detrending algorithm as a data preprocessing is compulsory.

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The detrending strategies allowed to extract from pressure raw data the periodic component that was masked by non-periodic effects, and thus enhanced the quality of the derivative. Based on the results, the adequate detrending strategies for each scenario are listed below:

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- in presence of a significant pressure decline, either due to reservoir depletion or constant well interference, all the considered strategies are effective.
- if a significant initial transient is observed, because of rate history prior to the test (es. $q_0 \ll q_2$), method 2 or method 3 can be successfully adopted.
- if any oscillation cycle (or hemicycle) is significantly altered by an interfering well, method 1 or method 2 can be adopted to allow the exclusion of anomalous cycle(s) from the Fourier analysis.
- if any hemicycle is significantly longer/shorter than the design, as in the case of a temporary suspension of the test, detrending with method 1, method 2 or method 3 allows the exclusion of the redundant parts of the hemicycle(s)/the exclusion of the short cycle(s) from the Fourier analysis.

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4. Materials and Methods

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Detrending refers to methodologies aimed at removing from a time series any trend that can mask or affect the information of interest. In the case of HPT, detrending refers to recognizing a non-periodic depletion trend and removing it from the pressure signal to isolate the pure periodic component. The four detrending methodologies, discussed in this paper do not require any model or parameter characterization. They are based on the observation of the pressure data only (methods 0 and 1, or on the observation of the pressure and rate data (methods 2 and 3), and they try to approximate or reconstruct the non-periodic component of the pressure signal.

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Let us consider a harmonic squared rate production history as shown in Fig.11 and the corresponding pressure response. T is the period of the harmonic signal. According to the terminology adopted in the oil industry for well testing, $T/2$ corresponds to the duration of each flow period. The rates adopted to impose the harmonic oscillation will be indicated as q_1 and q_2 , whereas q_0 refers to the last historical rate preliminary to the HPT. In the adopted nomenclature, n_T is the total number of periods T . If q_0 is null initial static conditions are assumed at the beginning of the test; furthermore, $q_2 = 0$ implies that the HPT is defined as a sequence of Draw Down (DD with $q_1 > 0$) and Build Up (BU $q_2 = 0$). Therefore, the initial transient state magnitude associated to the first flow period is comparable to the transient state magnitude associated with the following DDs. Whenever q_0 is null but neither q_1 nor q_2 are null, the harmonic pressure oscillation is influenced by an initial transient characterized by an amplitude higher with respect to the subsequent oscillations. The magnitude of the initial transient affects mainly the first DD and progressively attenuates during the test. When the HPT is superimposed onto ongoing production (i.e.: $q_0 \neq 0$, no well shut in before the test is imposed) the magnitude of the initial transient is proportional to the difference between the previous rate before the test (q_0) and the second test rate (q_2). In the following paragraphs we will assume $q_1 > q_2$ and therefore we will refer to q_1 as q_{max} and q_2 as q_{min} . Furthermore, we assume $q_{max} > q_0$.

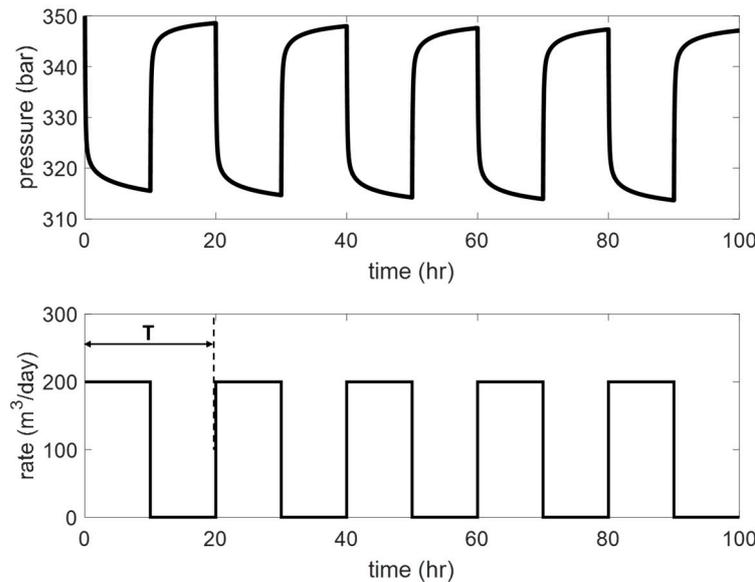


Fig.11: Example of HPT starting from static pressure with $q_{\min} = 0$

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292 4.1 Method 0: Linear detrending

293 Linear detrending is an adequate strategy in scenarios dominated by depletion, either due to
 294 late time effects (boundaries) or to field activities; however, it is not able to filter the initial transient
 295 due to the difference between the last rate preceding the test and the rate of the second hemicycle of
 296 oscillation. In the analyzed scenarios, the linear trend parameters (slope and known term) are
 297 obtained by least square fitting of pressure data.

298 4.2 Method 1: Ahn & Horne Approach

299 The methodology proposed by Ahn and Horne ([35]) is based on pressure data only and does
 300 not require information on petrophysical properties and fluid parameters. The algorithm was
 301 designed to detrend HPT pressure signals similar to the example in Fig. 11, therefore, assuming both
 302 q_0 and q_{\min} are equal to zero. The approach suggested by Ahn and Horne consists in generating an
 303 approximation of the constant rate pressure trend $g(t)$ at each time $t_n = \frac{2n+1}{2}T$ for $n = 1, \dots, n_T-1$ and
 304 linearly interpolating $g(t)$ between each couple of points t_{n-1} , t_n . The algorithm is:

$$g(t_n) = h(t_n) + h\left(t_n - \frac{T}{2}\right), \quad (1)$$

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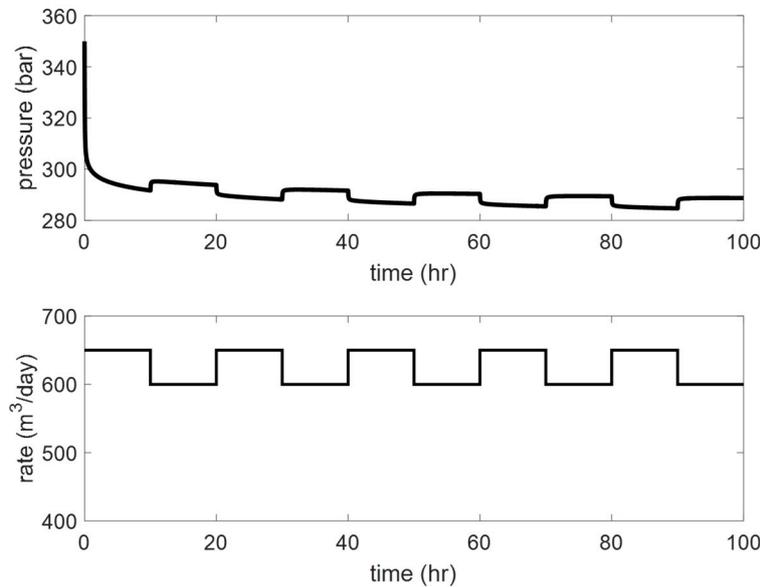
306 where $h(t_n)$ and $g(t_n)$ denote the observed periodic pulse and the constant rate approximation
 307 respectively at a time t_n .

308 Notice the suggested approach does not require any information on the value of the rate
 309 produced during the Draw Down periods but this implies that the production history is assumed to
 310 be an alternation of production/injection periods (Draw Down or Injection) and well shut in (Build
 311 Up or Fall Off). Consequently, it was not designed to detrend a pressure signal generated for $q_{\min} \neq$
 312 q_0 when the amplitude of the first transient can be significant, especially if $|q_{\max} - q_0| \gg$
 313 $|q_{\max} - q_{\min}|$. However, in scenarios where $|q_{\max} - q_0| \approx |q_{\max} - q_{\min}|$ detrending is not strictly
 314 necessary unless significant reservoir depletion, due to production from other wells, is observed.

315 4.3 Method 2: Rate Generalized Approach with stepwise linear interpolation

316 A new algorithm that provides an extension to the approach proposed by Ahn and Horne for
 317 any possible combination of q_{\min} and q_{\max} was derived by the authors. The algorithm represents the
 318 first step of the implementation of the approach proposed by Viberti (Viberti, 2016). Let us consider

319 the pressure signal associated to an HPT characterized by q_{\min} different from 0 and the maximum rate
 320 significantly higher with respect to the rate variation (see Fig. 12). The goal of the algorithm consists
 321 in calculating the reconstructed pressure signal corresponding to a constant rate equal to q_{\max} for a
 322 time vector containing the elements $t_n = \frac{1}{2}T, T, \frac{3}{2}T, 2T, \dots, n_T T$.
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325 Fig.12: Example of HPT starting from static pressure with $q_{\min} \neq 0$

326 In order to take into account the first transient due to the condition $|q_{\max} - q_0| \gg |\Delta q|$, where
 327 $\Delta q = q_{\max} - q_{\min}$, a normalized periodic rate variation is defined as:

$$\tilde{q} = \frac{\Delta q}{q_{\max}}, \quad (2)$$

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329 Adopting $g(t)$ and $h(t)$ as for the Ahn and Horne approach, and considering, as a simplified
 330 example, an HPT characterized by a $n_T = 2$, it is possible to write a system of linear equations so that:
 331

$$\begin{cases} h\left(\frac{1}{2}T\right) = q_{\max}g\left(\frac{1}{2}T\right) \\ h(T) = q_{\max}g(T) - \Delta qg\left(\frac{1}{2}T\right) \\ h\left(\frac{3}{2}T\right) = q_{\max}g\left(\frac{3}{2}T\right) - \Delta qg(T) + \Delta qg\left(\frac{1}{2}T\right) \\ h(2T) = q_{\max}g(2T) - \Delta qg\left(\frac{3}{2}T\right) + \Delta qg(T) - \Delta qg\left(\frac{1}{2}T\right) \end{cases} \quad (3)$$

332

333 The System of linear equations can be easily written as in (4) and solved through matrix
 334 inversion in order to find all the $g\left(i\frac{T}{2}\right)$ with $i=1, \dots, 2n_T$.
 335

$$\begin{bmatrix} h\left(\frac{1}{2}T\right) \\ h(T) \\ h\left(\frac{3}{2}T\right) \\ h(2T) \end{bmatrix} = \Delta q \begin{bmatrix} 1/\tilde{q} & 0 & 0 & 0 \\ -1 & 1/\tilde{q} & 0 & 0 \\ 1 & -1 & 1/\tilde{q} & 0 \\ -1 & 1 & -1 & 1/\tilde{q} \end{bmatrix} \begin{bmatrix} g\left(\frac{1}{2}T\right) \\ g(T) \\ g\left(\frac{3}{2}T\right) \\ g(2T) \end{bmatrix} \quad (4)$$

336

337 An approximation of the constant rate pressure signal is then obtained through linear
338 interpolation between any couple of values $g\left(i\frac{T}{2}\right)$ and $g\left((i-1)\frac{T}{2}\right)$.

339 4.4 Method 3: Rate Generalized Approach with full heuristic reconstruction

340 Method 3 overcomes the simplified assumption of linear interpolation adopted by method 2 and
341 provides a heuristic reconstruction of the constant rate pressure signal for all the elements of the
342 original time and pressure vectors for any periodic rate history and therefore also for $|q_{max}| \gg$
343 $|q_{max} - q_{min}|$. The algorithm derivation and details have been already published ([34]) and are here
344 briefly summarized. The algorithm is based on the identification of recurring events (therefore
345 characterized by periodicity) from a sequence of observations. As a consequence, it is based on the
346 analysis of all the semi-periods of a periodic signal at the same Δt in all the intervals $i\frac{T}{2} \leq \Delta t <$
347 $(i+1)\frac{T}{2}$. To do that, a dimensionless time variable $\chi \in \mathbb{R}$ is defined so that $t = \chi\frac{T}{2}$, therefore $\chi \in$
348 $[0, 2n_T]$.

349 The observations and the sought constant rate response can be written as $h(\chi, T)$ and $g(\chi, T)$
350 respectively and, adopting the definition of \tilde{q} introduced for method 2, observation at each recurrent
351 Δt can be expressed as $h\left((\chi-j)\frac{T}{2}\right)$ writing a system of $2n_T$ equations with $j = 0, \dots, 2n_T - 1$, so
352 that:

$$h\left((\chi-j)\frac{T}{2}\right) = \tilde{q}g\left((\chi-j)\frac{T}{2}\right) + \sum_{i=j+1}^{2n_T-j-1} -1^i g\left((\chi-i)\frac{T}{2}\right), \quad j = 0, \dots, 2n_T - 1, \quad (5)$$

353 The obtained system of linear equations can then be easily solved. The resulting constant rate
354 pressure signal is multiplied by a proper rate value and subtracted to the original pressure signal in
355 order to obtain the detrended harmonic pressure component.
356

357 5. Conclusions

358 For cases in which conventional well tests are not doable, be it that interruption of reservoir
359 production or production from the tested well is out of the question, a complementary well test
360 methodology, named Harmonic Pulse Test (HPT), has been designed. Nonetheless, HPT should not
361 be seen as a replacement for standard or conventional well testing, but rather as a valid option for
362 cases like the aforementioned. To make the best of the information given by the interpretation of an
363 HPT in the frequency domain, the aperiodic pressure decline trend due to initial transient, well
364 interference, reservoir production, boundaries, etc., should be recognized/reconstructed and
365 removed from the pressure signal to identify, in theory, the pure periodic component. The application
366 of detrending methodologies can offer an approximation of the periodic component of a pressure
367 signal. Authors presented four detrending methodologies which were discussed, compared and
368 validated by their application to several synthetic cases as well as a real case, each representing a
369 possible scenario featuring criticalities that could affect and reduce the reliability of the interpretation
370 process of an HPT. The different methodologies were compared in terms of derivative of the
371 amplitude ratio on the log-log plot.

372 Results clearly showed that for certain critical scenarios, the application of detrending
373 methodologies is necessary to avoid misleading results from the interpretation of test raw data.
374 Furthermore, polynomial detrending (Method 0) is effective in removing the pressure trend induced
375 by field depletion and constant well interference but cannot deal with transient effect related to
376 preexisting rate history or ongoing production changes. Conversely, the detrending algorithms based
377 on a heuristic approach, i.e. method 2 and method 3, are very effective to remove both. Finally, the
378 analysis of detrended data can be further improved by excluding anomalous cycles, i.e. cycles that
379 do not respect the designed test periodicity, such as in the case of well interference and/or temporary
380 interruption of the pressure pulses during the execution of the test. This result was confirmed by
381 application of the detrending algorithm to a real HPT on a gas storage well, during which the data

382 periodicity was compromised by temporary interruptions due to operational constraints; data pre-
383 processing ensured preservation of pressure periodicity, thus enhancing the quality of the derivative
384 of low frequency harmonic components (corresponding to middle time in the conventional
385 derivative).

386 Finally, the quality of the results from HPTs can be considerably improved by adopting an
387 effective detrending strategy and by doing so there is the real possibility of overcoming the limitation
388 in applicability of HPTs due to the difficulty of imposing a regularly pulsing rate for the whole test
389 duration (typically lasting several days). In other words, detrending offers the opportunity of making
390 HPTs appealing for well performance monitoring, which is particularly important for gas storage
391 filed management.

392

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