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Power Properties of Linearity Tests for Time Series

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Abstract. *This paper examines the power properties of several linearity tests applied in time-series analysis. The tests are the ones Lee et al. (1993) used in their Monte Carlo study. The main tool used for power comparisons in this paper is the Pitman asymptotic relative efficiency. The results generally strengthen the outcome of the simulations and complement some results in Lee et al. (1993). They also suggest guidelines for designing Monte Carlo experiments for linearity tests.*

Keywords. Bilinear model, local asymptotic power, nonlinear time series, Pitman asymptotic relative efficiency, threshold autoregressive model.

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1 Introduction

With increasing interest in nonlinear time-series models, testing linearity against nonlinearity has become an important issue in time-series analysis; see Granger and Teräsvirta (1993, chapter 6) for an overview. Recently, Lee, White, and Granger (1993), henceforth LWG, conducted a wide array of simulation experiments to study the power properties of a few linearity tests against different types of nonlinearity, including bivariate nonlinear models. Another study with a similar aim is Luukkonen, Saikkonen, and Teräsvirta (1988a). The main purpose of the present paper is to demonstrate that most of the simulation results of LWG can be explained or further illuminated using linearization and statistical theory, and, particularly, the concept of Pitman asymptotic relative efficiency (ARE). This theory can also be used when designing new simulation experiments. The plan of the paper is as follows. Section 2 briefly discusses most of the tests LWG considered by means of auxiliary regressions. Section 3 discusses the concept of ARE. Section 4 considers power properties of tests applied to Block1 models of LWG, and section 5 contains final remarks.

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2 Linearity Tests

I shall concentrate on the Block1 models in LWG. For this purpose, consider the following artificial model:

$$y_t = a_0 + \sum_{j=1}^{k} a_j z_t^j + u_t, \qquad u_t \sim \text{nid}(0, \sigma^2). \tag{2.1}$$

If either $z_t = y_{t-1}$ (univariate models) or $z_t = x_t$ (bivariate models), $a_0 = 0$, $k = 2$, then the F test of $a_2 = 0$ is TSAY1 (Tsay, 1986) as in LWG. If $k = 3$ and the above holds except that I assume $a_0 \neq 0$, the F test of $a_2 = a_3 = 0$ is a Lagrange-multiplier-type test of linearity against the hypothesis that the true model is a single hidden-layer artificial neural network model, as discussed in Teräsvirta, Lin, and Granger (1993). This test often has better power than the test LWG preferred, which is based on the same neural network model. However, when the true model is not a single hidden-layer neural network model, there are situations in which the test in Teräsvirta et al. (1993) is less powerful than the test in LWG and is not even consistent. A simple example is the model $y_t = a_4 y_{t-1}^4 + u_t$, $u_t \sim \text{nid}(0, \sigma^2)$, because the test in Teräsvirta et al. (1993) is only based on the first three moments and cross-moments of lags of y_t. In this paper, I nevertheless take that test to represent the neural network (NN) test. The reason is that many nonlinear models simulated in LWG may at least locally in a neighborhood of the null of linearity be approximated by a model resembling equation (2.1). As will be seen, comparing (2.1) to such a representation makes it possible to find an explanation for the fact that the NN test sometimes seems to have better power than some other linearity tests.

Furthermore, if $z_t = f_t$ where f_t is the OLS fit of the linear model $y_t = a y_{t-1} + u_t$, the F test of $a_j = 0$, $j \geq 2$, in equation (2.1), assuming $a_0 = 0$ is RESET (Ramsey, 1969). For Block1 models, $f_t = \hat{a} y_{t-1}$ (or $f_t = \hat{a} x_{t-1}$), so that f_t can be replaced by y_{t-1} (or x_t). If $k = 3$, RESET thus coincides with the auxiliary regression version of the NN test, except that $a_0 = 0$. The Keenan test (Keenan, 1985) is a special case of RESET such that $k = 2$, and for Block1 models the test is thus identical to TSAY1. LWG, however, carry out RESET differently. In their version, $z_t = y_{t-1}$, $z_t^j = \beta_j' w_t$, $j = 2, \ldots, k$, in equation (2.1), where: $w_t = (y_{t-1}^2, \ldots, y_{t-1}^k)'$ and $\beta_j' w_t$ is the t-th element of the j-th principal component of $W = (w_1', \ldots, w_T')'$. For bivariate models, x_t takes the place of y_{t-1}.

Next, consider the auxiliary regression

$$y_t = a y_{t-1} + c_1 u_{t-1} + c_{11} u_{t-1} y_{t-1} + c_{12} u_{t-1} y_{t-2} + c_{112} u_{t-1} y_{t-1} y_{t-2} + u_t,\ u_t \sim \text{nid}(0, \sigma^2). \tag{2.2}$$

The χ^2 (Lagrange multiplier, or LM) test of $c_1 = c_{11} = c_{12} = c_{112} = 0$ in equation (2.2) is WHITE3 of LWG. For the origins of this test, see White (1987). The lagged errors are replaced by their estimates from the OLS regression of y_t on y_{t-1}. Note that the test is not a pure linearity test, as the alternative also contains a first-order moving average term. This explains the results for White tests in Table 5 of LWG for Model1 of Block2. Of the remaining tests, TSAY2 (another version of the test of Tsay, 1986) requires an auxiliary regression with 16 regressors, 15 of which have zero coefficients under the null of linearity. These auxiliary regressions form a starting point for considering and comparing the power of different tests.

3 Asymptotic Relative Efficiency

To introduce the concept of Pitman asymptotic relative efficiency (ARE), I consider two nonlinear models and assume that one of them has generated the data. This model is characterized by the log-likelihood function

$$q_T(a, \phi) = \sum_{t=1}^{T} \bar{q}_t(a, \phi), \tag{3.1}$$

where a is a $p \times 1$ and ϕ an $s \times 1$ parameter vector, and T is the sample size. The other (misspecified or inappropriate) model is characterized by the log-likelihood function $p_T(a, \psi) = \sum_{t=1}^{T} \bar{p}_t(a, \psi)$, where ψ is an $r \times 1$ parameter vector. Generally, $p_T(a, \phi) \neq q_T(a, \psi)$, but $p_T(a, 0) = q_T(a, 0)$. I want to test $\text{H}_{0\psi} : \psi = 0$ against $\text{H}_{1\psi} : \psi \neq 0$, whereas the relevant null hypothesis is $\text{H}_{0\phi} : \phi = 0$ against $\text{H}_{1\phi} : \phi \neq 0$, because equation (3.1) characterizes the true model. Consider a sequence of local alternatives $\phi = \delta / T^{\frac{1}{2}}$, $\delta \neq 0$, so that the data are generated by a model with the log-likelihood function $q_T(a, \delta / T^{\frac{1}{2}})$. Define

$$\bar{k}_t = \left[\{\partial \bar{p}_t(a, 0)/\partial a\}' \ \{\partial \bar{p}_t(a, 0)/\partial \psi\}' \ \{\partial \bar{q}_t(a, 0)/\partial \phi\}' \right]$$

with covariance matrix $\Sigma = E\bar{k}_t\bar{k}_t' = [\Sigma_{ij}]$, $i, j \in \{a, \psi, \phi\}$, where the partition conforms to that of $\bar{k}_t$. Then the asymptotic distribution of the LM test of $H_{0\psi}$ ($LM_{0\psi}$) follows an asymptotic χ^2_r distribution with noncentrality parameter $\lambda_\psi(a, \delta) = \delta'\Sigma_{\phi\psi\cdot a}\Sigma^{-1}_{\psi\psi\cdot a}\Sigma_{\psi\phi\cdot a}\delta$, where $\Sigma_{ij\cdot k} = \Sigma_{ij} - \Sigma_{ik}\Sigma^{-1}_{kk}\Sigma_{kj}$ (see Saikkonen [1989] or Luukkonen et al. [1988a]). On the other hand, the asymptotic distribution of the LM test of $H_{0\phi}$ is a noncentral χ^2_s distribution with noncentrality parameter $\lambda_\phi(a, \delta) = \delta'\Sigma_{\phi\phi\cdot a}\delta$. The asymptotic relative efficiency of $LM_{0\psi}$ is the following ratio (Saikkonen, 1989):

$$\mathrm{ARE}_\psi(a, \delta, \alpha, \beta) = \frac{\lambda_\psi(a, \delta)d(s, \alpha, \beta)}{\lambda_\phi(a, \delta)d(r, \alpha, \beta)} \ . \tag{3.2}$$

In equation (3.2), $d(h, \alpha, \beta)$ is the noncentrality parameter of a noncentral χ^2_b distribution, such that the $1{-}\beta$ fractile of that distribution and the $1{-}\alpha$ fractile of the (central) χ^2_b distribution coincide. Values of $d(h, \alpha, \beta)$ are tabulated, for example, in Pearson and Hartley (1972, Table 25). If $r = s$, equation (3.2) does not depend on d. If $r = s = 1$, ARE is also independent of δ. If $\lambda_\psi(a, \delta) = 0$, the asymptotic power of LM_ψ against the local alternative equals the size of the test. It is worth noting already that the McLeod-Li test that LWG considered has this property for all models included in Block1, as is clear from Luukkonen et al. (1988a).

4 Interpreting Simulation Results

I shall now consider the simulation results of Block1 models in LWG using the auxiliary regression interpretation of TSAY1, TSAY2, the NN test, RESET, and WHITE3. The nonlinear models in Block2 consist of another bilinear model and two nonlinear moving-average models. The latter type are rarely applied in practice. For this reason, the focus will be on Block1 models.

The Threshold Autoregressive (TAR) model

Consider the following nonlinear model:

$$y_t = a_0 y_{t-1} + a_1 F_1(y_{t-1}) + a_2 F_2(y_{t-1}) + u_t, \tag{4.1}$$

where

$$F_j(y_{t-1}) = (1 + \exp\{-\gamma(y_{t-1} - c_j)\})^{-1} - \frac{1}{2}, \qquad j = 1, 2, \quad \gamma > 0, \quad c_1 < c_2. \tag{4.2}$$

LWG simulated equation (4.1) with $a_0 = 0.3$ and $a_1 = -a_2 = 1.2$ when $c_1 = -c_2 = -1$ and $\gamma \to \infty$ in equation (4.2). To study the performance of the tests, I linearize equation (4.1). An appropriate way of doing this is to replace F_j by a third-order Taylor expansion about $\gamma = 0$, because equation (4.1) is linear when $\gamma = 0$.

The third-order Taylor expansion to F_j is:

$$\begin{aligned} T_j(y_{t-1}) \ &= \ b_1(y_{t-1} - c_j) + b_3(y_{t-1} - c_j)^3 = b_3 y^3_{t-1} - 3b_3 c_j y^2_{t-1} \\ &\quad + (3b_3 c_j^2 + b_1)y_{t-1} - c_j(b_3 c_j^2 + b_1), \qquad j = 1, 2, \end{aligned} \tag{4.3}$$

where $b_1 = \gamma/4$ and $b_3 = \gamma^3/16$. Assuming $a_1 = -a_2$ and $c_1 = -c_2$ yields

$$\begin{aligned} \{a_1 T_1(y_{t-1}) + a_2 T_2(y_{t-1})\}y_{t-1} \ &= \ a_1\{T_1(y_{t-1}) - T_2(y_{t-1})\}y_{t-1} \\ &= \ -6a_1 b_3 c_1 y^3_{t-1} - a_1(6b_3 c_1^3 - 2b_1 c_1)y_{t-1}. \end{aligned} \tag{4.4}$$

Thus the corresponding approximation of equation (4.1) is of the form:

$$y_t = a_1^* y_{t-1} + a_3^* y^3_{t-1} + u_t', \tag{4.5}$$

and the linearity hypothesis is $H_0' : a_3^* = 0$. The fourth- and second-order terms theoretically present in equation (4.4) vanish because both $a_1 = -a_2$ and $c_1 = -c_2$.

From equation (4.5) it is seen that the NN test has power against equation (4.1), as its auxiliary regression contains the crucial third-order term y^3_{t-1}. On the other hand, y^2_{t-1} in TSAY1 is a very poor substitute for y^3_{t-1}.

Assume equation (4.5) is the correct model, and equation (2.1) with $a_0 = 0$ and $k = 2$ is the inappropriate alternative. Then

$$\Sigma = E\bar{k}_t\bar{k}_t' = \begin{bmatrix} Ey_{t-1}^2 & Ey_{t-1}^3 & Ey_{t-1}^4 \\ & Ey_{t-1}^4 & Ey_{t-1}^5 \\ & & Ey_{t-1}^6 \end{bmatrix}$$

so that $\Sigma_{\phi\psi} = Ey_{t-1}^5 = 0$, which implies $\Sigma_{\phi\psi\cdot a} = 0$. Thus for any $|a_1^*| < 1$, $\lambda_\psi(a_1^*, \delta) = 0$, so that the local asymptotic power of TSAY1 against equation (4.5) is not higher than the size of the test. This explains the low empirical power of the test.

Next I apply ARE to consider the performance of WHITE3. Assume again that equation (4.5) is the true model. If I choose $\alpha = 0.05$ and $\beta = 0.5$, say, then the ARE of WHITE3 with respect to equation (4.5) is:

$$\text{ARE}_W(a_1, \delta, 0.05, 0.5) = 1.896a_1^2(1 - a_1^2), \tag{4.6}$$

so that

$$\max_{|a_1|<1} \text{ARE}_W(a_1, \delta, 0.05, 0.5) = 0.474 \text{ at } a_1 = \pm 1/\sqrt{2},$$

and $\text{ARE}_W(0.3, \delta, 0.05, 0.5) = 0.155$. The computation of equation (4.6) (see the Appendix) shows that the only term in WHITE3 based on equation (2.2) that contributes to the (local) power is the third-order term $y_{t-1}y_{t-2}\hat{u}_{t-1}$. The test thus may be expected to detect nonlinearity in equation (4.1) for $a_1 = 0.3$ because equation (4.5) is a local approximation to (4.1) in the neighborhood of $\gamma = 0$. However, for the present parametrization, a much larger sample size than T = 200 is needed for that power to show. Note that the RESET based on principal components is also without power, although the linear combinations serving as regressors in the test do contain y_{t-1}^3.

The Sign (SGN) model

The sign model of LWG is:

$$y_t = \text{sgn}(y_{t-1}) + u_t,\ u_t \sim \text{nid}(0, 1), \tag{4.7}$$

where $\text{sgn}(x) = 1$, $x > 0$; $\text{sgn}(x) = 0$, $x = 0$; $\text{sgn}(x) = -1$, $x < 0$.

Consider the generalization:

$$y_t = aF_H(y_{t-1}) + u_t, \tag{4.8}$$

where $F_H(y_{t-1}) = (1 + \exp\{-\gamma y_{t-1}\})^{-1} - \frac{1}{2}$, $\gamma > 0$. Choosing $a = 2$ and letting $\gamma \to \infty$ yields equation (4.7). Note that equation (4.8) is a special case of the single hidden-layer feedforward artificial neural network model (LWG; White, 1989) with a single hidden unit. The NN test of $H_0 : a = 0$ is therefore powerful by definition. Replacing $F_H(y_{t-1})$ in equation (4.8) by its third-order Taylor approximation about $\gamma = 0$ (linearity) yields $y_t = b_1y_{t-1} + b_3y_{t-1}^3 + u_t'$.

The arguments used above apply again. TSAY1 has little power because it lacks y_{t-1}^3. In fact, its empirical power in the experiments of LWG does not increase with the sample size. The ARE of the White test equals zero for $\alpha = 0.05$ and $\beta = 0.5$, which explains its lack of power. For comparison, RESET with principal components is clearly now more powerful than in the previous design.

Bivariate models

The above considerations also help explain the simulation results for the two bivariate models. For the SQ model $y_t = x_t^2 + u_t$, TSAY1 is the best test. The regression version of the neural network test indicates that the NN test of LWG is not as powerful, but may still have considerable power. Taking $y_t = ax_t + bx_t^2 + u_t$ to be the true model, it is easy to see that the asymptotic local power of WHITE3 is not higher than the size of the test because $\Sigma_{\phi\psi} = 0$. This is because x_t and u_{t-j} are independent at any lag j. Nevertheless, the empirical global power of WHITE3 is fairly high. This helps to put the performance of the BDS test into perspective. Its empirical power is high, but no higher than that of a test whose ARE equals zero. However, a problem with this test is that its size is not completely under control in small samples. This is because its asymptotic null

distribution depends on two nuisance parameters: the embedding dimension and the nearness parameter; see for example Brock and Potter (1993). In fact, as to the SQ model, Table 8 in LWG is more informative than Table 4. The differences in power one may expect appear more clearly when the error standard deviation $\sigma = 20$. TSAY1 is then the most powerful test, followed by the NN test. The power of WHITE3 is low.

The power of the linearity tests against the model EXP($y_t = \exp(x_t) + u_t$) is best evaluated by approximating the exponent by a Taylor expansion. This shows that TSAY and the NN test should be the most powerful tests, and that both x_t^2 and x_t^3 are useful terms in the auxiliary regression. From Table 9 in LWG it is seen that TSAY1 and the NN test have about the same empirical power. Assuming that the true model is $y_t = ax_t + bx_t^2 + cx_t^3 + u_t$ and selecting equation (2.2) with $z_t = x_t$ to be the inappropriate one again gives $\Sigma_{\phi\psi} = 0$. This leads one to expect WHITE3 to be clearly less powerful than the other two tests, which also turns out to be the case.

Bilinear model

LWG simulated the (Block1) bilinear model

$$y_t = ay_{t-1} + c_{ij}u_{t-i}y_{t-j} + u_t, \qquad u_t \sim \text{nid}(0, \sigma^2), \tag{4.9}$$

where $i = 2$, $j = 1$, $a = 0$ and $c_{21} = 0.7$. WHITE3 had the highest power. As seen from equation (2.2), its auxiliary regression does not contain $u_{t-2}y_{t-1}$. To find out where the power comes from, I consider two misspecified models based on WHITE3, both of type (4.9). The idea is to separately consider contributions of different components to the power of the test in the WHITE3 equation (2.2). The first model has $i = j = 1$ and $c_{11} \neq 0$, whereas the second one has $i = 1$, $j = 2$ with $c_{12} \neq 0$. The ARE of the linearity test of $c_{11} = 0$ in the first misspecified model when the data were generated by equation (4.9) is:

$$\text{ARE}_1(a) = 4a^2(1 - a^2)^2/\{(1 + 2a^2 - 2a^4)(3 - 2a^2)\},$$

whereas that of the second inappropriate model equals

$$\text{ARE}_2(a) = (1 - a^2)^2/(1 + 2a^2 - 2a^4)$$

(see the Appendix). Now, $\text{ARE}_2(0) = 1$, indicating that the component $u_{t-1}y_{t-2}$ in the White tests is important, contributing power as $a = 0$ in equation (4.9). The McLeod-Li test also has high power, although its ARE compared to the test based on the true model (4.9) equals zero. The low power of TSAY1 therefore requires an explanation. It is sufficient to look at its ARE with respect to the test based on equation (4.9), which is:

$$\text{ARE}_{T1}(a) = 3a^2(1 - a^2)/(1 + 2a^2 - 2a^4) = 0,$$

for $a = 0$ (see the Appendix). On the other hand, TSAY2 is more powerful than TSAY1 although it contains more regressors. This suggests that some of the additional lags introducing cross-terms in the auxiliary regression of the Tsay test increase the power of the test. To investigate this, consider the following simple artificial model:

$$y_t = ay_{t-1} + c_{12}y_{t-1}y_{t-2} + u_t, \qquad u_t \sim \text{nid}(0, \sigma^2). \tag{4.10}$$

The ARE of the test of $c_{12} = 0$ in equation (4.10) compared to that of $c_{21} = 0$ in equation (4.9) equals

$$\text{ARE}_T(a) = (1 - a^2)(1 + 2a^2)/(1 + 2a^2 - 2a^4),$$

so that $\text{ARE}_T(0) = 1$. Thus, adding the second lag is likely to increase the power of the Tsay test substantially. TSAY2 uses five lags, which reduces the power again because many of the terms in the auxiliary regression of TSAY2 are redundant if one tests $c_{21} = 0$ in equation (4.3). A larger sample size and/or more noise in equation (4.9) would be needed to render TSAY2 more powerful than the McLeod-Li test. Note that the ARE of TSAY1 is maximized at $a = \pm 1/\sqrt{2}$, and the maximum equals $\frac{1}{2}$. Thus for $|a| = 1/\sqrt{2}$, TSAY1 would be clearly more powerful than the McLeod-Li test. The power of TSAY2 would decrease by increasing $|a|$ sufficiently as $\text{ARE}_T(1) = 0$.

The bilinear model constitutes an interesting example, because the McLeod and Li test with zero ARE compared to the test based on equation (4.9) is quite powerful. The ARE is based on local considerations, and

a test with zero ARE with respect to another test may still have plenty of power against a global alternative. The ARE thus does not necessarily say much about the empirical power of a test in a given experiment. What the ARE comparisons do is establish a ranking of tests in terms of power: for a given number of observations, a test with a higher ARE with respect to another test is expected to have more power than one with a lower ARE with respect to the same test.

This has implications for the design of simulation experiments. Assume that, in a pilot study, a test with zero ARE has high power (say, 0.9). Then one knows that the experiment will not be very informative about tests with higher ARE, because their power will only vary between 0.9 and unity. Suppose the experiment includes a test whose ARE is difficult or impossible to determine, and whose power turns out to lie between 0.9 and unity as well. Then it is difficult to say much about the relative performance of the test, because a test with zero ARE already is very powerful. In the present example, the BDS test is a case in point. It would be useful to redesign the experiment in such a way that the power of the tests with zero ARE would not be too high. This would allow more spread between powers of tests with zero ARE and those with high ARE, and give a better indication of the power properties of tests with unknown ARE. The designs in Block2 (Model5 and Model6) are not ideal in this respect either.

The argument also works the other way around. Suppose that in a simulation experiment the tests with high ARE have low empirical power. Then the tests with low ARE are even less powerful, and the results of the experiment probably turn out not to be particularly informative if power comparisons between tests are the main object of interest. To avoid that, and to ensure a sufficient amount of variation in the simulation results, tests with high ARE should be designed to have fairly high power. Alternatively, to obtain interesting information about power differences, the tests should be carried out at a sufficiently large number of sample sizes.

Nonlinear Autoregressive (NLAR) model

A linearization of the model indicates that TSAY1, TSAY2, the NN test, and RESET may have power against NLAR because their auxiliary regressions contain y_{t-1}^2. That of RESET also contains y_{t-1}^4, albeit in linear combinations with other powers of y_{t-1}. That the regressors give power is seen from Table 4 in LWG. However, TSAY2 has low power because it contains a large number of redundant regressors.

5 Final Remarks

I have shown that the simulation results in LWG can to a large extent be explained by linearizing some of the models and applying the concept of ARE. The following conclusions emerge. First, the mediocre performance of the TSAY1 against TAR and SGN models is due to the particular parametrization of these models. The designs in LWG did not include a two-regime TAR model, against which the Tsay test usually has power; see Luukkonen, Saikkonen, and Teräsvirta (1988b) and Petruccelli (1990) for examples. Second, the results of LWG speak against the principal component RESET, not RESET as such. For Block1 models, the original RESET with f_{t-1}^2 and f_{t-1}^3 as regressors is almost the same as the NN test in Teräsvirta et al. (1993), and should therefore have excellent power against the TAR and SGN models. Third, the design of the bilinear alternatives is not informative enough for evaluating the relative performance of the BDS test. In general, whenever the BDS test has high power, then at least one test with zero ARE with respect to the test based on the correct alternative also is quite powerful. The power of several tests against bilinearity crucially depends on the coefficient of y_{t-1}, which equals zero in all simulations of LWG. Luukkonen et al. (1988a) have made a similar point.

Finally, an LM or LM-type test against the appropriate alternative would be a useful addition to any Monte Carlo design. This is because it gives an upper bound to the empirical power for that particular design, and thus helps to better assess the relative performance of the other tests. In some cases LWG have already included it: an example is TSAY1 in the SQ model.

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Appendix: Computing Asymptotic Relative Efficiency

A1. True model $y_t = ay_{t-1} + c_{21}u_{t-2}y_{t-1}$; the inappropriate model $y_t = ay_{t-1} + u_t + \psi u_{t-1}y_{t-1}$

In all these cases, σ^2 may be regarded as known because the information matrix of σ^2 and the remaining parameters is block diagonal such that one block contains σ^2 and the other the rest of the variables. Then the components of $\bar{k}_t$ are:

$$\partial \bar{p}_t(a,0)/\partial a = -\sigma^{-2}\tilde{u}_t y_{t-1} \tag{A.1}$$

$$\partial \bar{p}_t(a,0)/\partial \psi = -\sigma^{-2}\tilde{u}_t \tilde{u}_{t-1} y_{t-1} \tag{A.2}$$

$$\partial \bar{p}_t(a,0)/\partial \phi = -\sigma^{-2}\tilde{u}_t \tilde{u}_{t-2} y_{t-1} \tag{A.3}$$

where $\tilde{u}_t = y_t - ay_{t-1}$. Then $r = s = 1$, $\Sigma_{ij} = \sigma_{ij}$ is a scalar, and

$$\Sigma = \begin{pmatrix} \sigma_{aa} & \sigma_{a\psi} & \sigma_{a\phi} \\ & \sigma_{\psi\psi} & \sigma_{\psi\phi} \\ & & \sigma_{\phi\phi} \end{pmatrix} = \sigma^{-2} \begin{pmatrix} \sigma_y^2 & 0 & 0 \\ & \sigma^2\sigma_y^2(3-2a^2) & 2a\sigma^4 \\ & & \sigma^2\sigma_y^2(1+2a^2-2a^4) \end{pmatrix}$$

where $\sigma_y^2 = Ey_t^2 = \sigma^2/(1-a^2)$. Thus $\sigma_{\psi\psi\cdot a} = \sigma_{\psi\psi}$ and $\sigma_{\phi\phi\cdot a} = \sigma_{\psi\psi}$, so that $\mathrm{ARE}_\psi(a) = \sigma_{\psi\phi}^2/\sigma_{\psi\psi}\sigma_{\phi\phi} = 4a^2(1-a^2)^2/\{(3-2a^2)(1+2a^2-2a^4)\}$.

A2. True model $y_t = ay_{t-1} + c_{21}u_{t-2}y_{t-1}$; the inappropriate model the auxiliary regression of TSAY1

The auxiliary regression of TSAY1 is:

$$y_t = ay_{t-1} + a_2 y_{t-1}^2 + u_t.$$

Then equations (A.1) and (A.3) remain unchanged, but equation (A.2) is replaced by $\partial \bar{p}_t(a,0)/\partial \psi = -\sigma^{-2}\hat{u}_t y_{t-1}^2$. It follows that

$$\Sigma = 4\sigma^{-2} \begin{pmatrix} \sigma_y^2 & 0 & 0 \\ & 3\sigma_y^4 & 3a\sigma^2\sigma_y^2 \\ & & \sigma^2\sigma_y^2(1+2a^2-2a^4) \end{pmatrix}$$

which leads to $\mathrm{ARE}_\psi(a_1) = 3a^2(1-a^2)/(1+2a^2-2a^4)$.

A3. True model $y_t = a_1 y_{t-1} + a_3 y_{t-1}^3 + u_t$; the inappropriate model equation (A.4)

The inappropriate model is based on WHITE3, and can be written as:

$$y_t = a_1 y_{t-1} + u_t + \psi_1 u_{t-1} + \psi_2 y_{t-1} u_{t-1} + \psi_3 y_{t-2} u_{t-1} + \psi_4 y_{t-1} y_{t-2} u_{t-1}, \tag{A.4}$$

where $u_t \sim \text{nid}(0, \sigma^2)$. This yields $\sigma^2 \Sigma_{aa} = \sigma_y^2$, $\sigma^2 \Sigma_{a\phi} = 3\sigma_y^4$, $\sigma^2 \Sigma_{\phi\phi} = 15\sigma_y^6$, and

$$\sigma^2 \Sigma_{\phi\phi \cdot a} = 6\sigma_y^6. \tag{A.5}$$

Furthermore,

$$\sigma^2 \Sigma_{\psi\psi} = \begin{pmatrix} \sigma^2 & 0 & 0 & a_1\sigma^2\sigma_y^2 \\ & 3\sigma^4 + a_1^2\sigma^2\sigma_y^2 & a_1\sigma^2\sigma_y^2 & 0 \\ & & \sigma^2\sigma_y^2 & 0 \\ & & & 3\sigma^2\sigma_y^4 \end{pmatrix}$$

$$\sigma^2 \Sigma_{a\psi} = (\sigma^2, 0, 0, 2a_1\sigma^2\sigma_y^2), \ \sigma^2 \Sigma_{\phi\psi} = (3\sigma^2, \sigma_y^2, 0, 0, 12a_1\sigma^2\sigma_y^4)$$

$$\sigma^2 \Sigma_{\phi\psi \cdot a} = \sigma^2(\Sigma_{\phi\psi} - \Sigma_{\phi a}\Sigma_{aa}^{-1}\Sigma_{a\psi}) = (0, 0, 0, 6a_1\sigma^2\sigma_y^4).$$

Thus the only term that contributes to the asymptotic local power of WHITE3 in this case is $y_{t-1}y_{t-2}\hat{u}_{t-1}$. Straightforward computation shows that the southeast corner element of $\sigma^{-2}\Sigma_{\psi\psi \cdot a}$ equals $(2\sigma^2\sigma_y^4)^{-1}$, so that

$$\lambda_\psi(a_1, \delta) = \delta' \Sigma_{\phi\psi \cdot a} \Sigma_{\psi\psi \cdot a}^{-1} \Sigma_{\psi\phi \cdot a}^{-1} \delta = 18 a_1^2 \sigma_y^4 \sigma^2.$$

Using equation (A.5), one obtains $\lambda_\psi(a_1, \delta) = 6\sigma^{-2}\sigma_y^6\delta^2$, so that $\lambda_\psi(a_1, \delta)/\lambda_\phi(a_1, \delta) = 3a_1^2(1 - a_1^2)$ and

$$\text{ARE}_\psi(\delta, a_1, \alpha, \beta) = 3a_1^2(1 - a_1^2)\{d(1, \alpha, \beta)/d(4, \alpha, \beta)\}.$$

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