Generalized Spectral Tests for Conditional Mean Models in Time Series with Conditional Heteroscedasticity of Unknown Form

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Economic theories in time series contexts usually have implications on and only on the conditional mean dynamics of underlying economic variables. We propose a new class of specification tests for time series conditional mean models, where the dimension of the conditioning information set may be infinite. Both linear and nonlinear conditional mean specifications are covered. The tests can detect a wide range of model misspecifications in mean while being robust to conditional heteroscedasticity and higher order time-varying moments of unknown form. They check a large number of lags, but naturally discount higher order lags, which is consistent with the stylized fact that economic behaviours are more affected by the recent past events than by the remote past events. No specific estimation method is required, and the tests have the appealing “nuisance parameter free” property that parameter estimation uncertainty has no impact on the limit distribution of the tests. A simulation study shows that it is important to take into account the impact of conditional heteroscedasticity; failure to do so will cause overrejection of a correct conditional mean model. In a horse race competition on testing linearity in mean, our tests have omnibus and robust power against a variety of alternatives relative to some existing tests. In an application, we find that after removing significant but possibly spurious autocorrelations due to nonsynchronous trading, there still exists significant predictable nonlinearity in mean for S&P 500 and NASDAQ daily returns.

1. INTRODUCTION

Nonlinear time series analysis has been advancing rapidly, with wide applications in economics and finance (e.g. Brock, Hsieh and LeBaron (1991), Granger and Teräsvirta (1993), Teräsvirta, Tjøstheim and Granger (1994b), Tjøstheim (1994), Granger (2001)). Like linear time series analysis, nonlinear time series modelling involves model identification, estimation and evaluation. Specification analysis is needed in model identification and evaluation. In this paper, we shall develop a new class of specification tests for conditional mean models in time series with conditional heteroscedasticity of unknown form.

Most economic theories in dynamic contexts, such as efficient market hypothesis, expectations hypothesis, consumption smoothing, dynamic asset pricing and rational expectations, have implications on and only on the conditional mean dynamics of underlying economic variables given the information available to economic agents (e.g. Cochrane (2001),
Sargent and Ljungqvist (2002)). For example, the conventional efficient market hypothesis states that the expected asset return given the information available, is zero, or at most, is constant over time (e.g. Fama (1970, 1991), Campbell, Lo and MacKinlay (1997, Chapter 1)), and dynamic asset pricing implies that the expectation of the pricing error given the information available is zero for all assets (Cochrane, 2001). Although economic theory may suggest a nonlinear relationship, it does not give a concrete functional form for the conditional mean of economic variables. Various parametric models used in practice can be, at best, regarded as approximations to the underlying conditional mean dynamics. There are many ways to specify which variables in the information set, which functional forms, and which lag structures to be used in conditional mean modelling. It is important to test conditional mean specification, because misspecification in mean can lead to misleading conclusions on economic theories and hypotheses, and to suboptimal point forecasts.

In time series modelling, it is important to determine first whether a time series is linear in mean; i.e. whether the conditional mean of a process is a linear combination of the variables in an information set. There have been a variety of tests for linearity in mean in the literature. They can be divided into two broad categories. One contains the tests derived without a specific nonlinear alternative. Examples include Keenan (1985), Tsay (1986) and White (1989). The other category consists of tests against a specific nonlinear alternative, usually formulated as Lagrangian Multiplier (LM) or LM-type tests. Examples include Luukkonen, Saikkonen and Teräsvirta (1988a,b), Saikkonen and Luukkonen (1988), Teräsvirta, Lin and Granger (1994a), Hamilton (2001), and Dahl and Gonzalez-Rivera (2003). The LM tests of Hamilton (2001) and Dahl and Gonzalez-Rivera (2003) are based on the random field theory. These tests contain a rich class of alternative models and can be interpreted as tests based on spline smoothers (Dahl, 2002). The greatest appeal of the tests in the second group is that they involve no estimation of the specified nonlinear alternative model, which could otherwise be computationally intensive. On the other hand, some tests in the first group can be interpreted as LM tests against a nonlinear alternative. Such interpretation is informative because it can reveal against which type of nonlinearity a test has the best power. Of course, some tests with unspecified alternatives do not have an LM test interpretation, although they have the best power against certain implicit alternatives.

When there is prior information about a potential alternative, or when one is interested in certain specific alternatives, tests against a specific alternative are a natural choice. This is exactly the case for the tests by Luukkonen et al. (1988a,b) and Saikkonen and Luukkonen (1988), where the interest is in modelling smooth regime changes. In practice, economic theory often does not point to a single nonlinear alternative. In such scenarios, it is desirable to have an omnibus test against general departure from linearity. Except White’s (1989) neural network test, which can detect all possible misspecified functional forms given a correct lag specification, other existing tests for linearity in mean are of parametric nature in the sense that they all test, explicitly or implicitly, a parametric alternative with a fixed lag specification. These tests have optimal power against a specific alternative but they may have low or little power against other alternatives.

In this paper, we propose a class of generally applicable omnibus tests for time series conditional mean models, with no prior knowledge of possible alternatives (including both functional forms and lag structures). Both linear and nonlinear conditional mean models are covered in a unified set-up. We use the generalized spectrum, which was proposed in

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1. In some circumstances, economic theory may suggest certain restrictions on the functional form and/or the lag structure of the conditional mean dynamics of an underlying process. For example, Hall’s (1978) consumption smoothing hypothesis suggests that the expectation of the next period’s marginal utility of consumption given the information available at the current period is a function of the current period consumption only. However, the functional form is not specified unless the utility function of the representative economic agent is known.
Hong (1999) as a new analytic tool for nonlinear time series. Thanks to the use of the
characteristic function, the generalized spectrum can capture both linear and nonlinear serial
dependence. The latter can be subtle and difficult to detect using conventional econometric tools.
In the meantime, the generalized spectrum enjoys the nice features of spectral analysis. In
particular, it incorporates information on the serial dependence from all lags and can characterize
cyclical dynamics caused by linear or nonlinear serial dependence. Thus, our approach can detect
a wide variety of misspecifications in both functional form and lag structure. This distinguishes
our tests from the existing tests for time series conditional mean models, all of which assume a
fixed lag order specification and focus on the functional form misspecification. One important
feature of time series conditional mean modelling is that the conditioning information set usually
contains an infinite number of lags (i.e. the entire past history), unless a Markovian assumption
holds. Our tests check a large number of lags without suffering from the curse of dimensionality.
When a large number of lags is used, chi-square tests for linearity usually have poor power
in finite samples, due to the loss of a large number of degrees of freedom (see, e.g. Dahl and
Gonzalez-Rivera, 2003, for more discussion). This undesired feature, fortunately, is not shared
by our generalized spectral approach, because it naturally discounts higher order lags, which is
consistent with the stylized fact that economic behaviours are usually more influenced by the
recent events than by the remote past events. Thus, our tests are particularly useful when the
information set has a large dimension. We note that our tests can be used to test the martingale
hypothesis for observed raw data without any modification.

It should be emphasized that Hong’s (1999) generalized spectrum itself cannot be used
to test conditional mean specification, because it can capture the serial dependence in every
conditional moment and thus cannot separate the serial dependence in mean from that in higher
order moments. However, because the characteristic function can be differentiated to generate
moments, a suitable generalized spectral derivative enables us to focus only on the serial
dependence in mean, making it suitable to test conditional mean specification. We compare a
nonparametric (inefficient) generalized spectral derivative estimator with a restricted (efficient)
counterpart implied by correct conditional mean specification. Our tests can be viewed as a
generalization of Hausman’s (1978) method from a parametric context to a nonparametric time
series context, although the asymptotic theory is different.

Most existing tests for time series conditional mean models assume observable explanatory
variables. In contrast, our tests can check various linear and nonlinear parametric conditional
mean models with possibly unobservable variables (e.g. past shocks) and an infinite number of
lags. Examples include ARMA models, ARMAX models, regime-switching models (Hamilton,
1989), state-space models (Priestley, 1988), smooth transition autoregressive models (Teräsvirta,
1994), Poisson jump models, and threshold autoregressive models with known thresholds (Tiao
and Tsay (1994), Potter (1995)). Our procedures only require as inputs estimated model residuals,
obtained from any \( \sqrt{T} \)-consistent parameter estimates. We note that compared to the vast
literature on testing linearity in mean, there are relatively few tests for nonlinear time series
conditional mean models. Exceptions are Tsay (1989), Eitrheim and Teräsvirta (1996), Hamilton

Economic theory, while having implications on the conditional mean dynamics of an
underlying process, is usually silent about its higher order conditional moment dynamics. Thus,
as emphasized by Granger (1995), it is important to develop tests of conditional mean models that
are robust to conditional heteroscedasticity and other higher order time-varying moments. Failure
to accommodate conditional heteroscedasticity will lead to improper levels for the tests, giving

2. There has been an increasing interest in using the characteristic function in econometrics (e.g. Epps (1987,
1988), Pinkse (1998), Singleton (2001), Jiang and Knight (2002), Knight and Yu (2002), and Chacko and Viceira (2003)).
a misleading conclusion. For example, an ARCH process is similar to a bilinear autoregressive process in terms of autocorrelations in level and level-square, respectively (Bera and Higgins, 1997). A LM test for a bilinear alternative will be likely to mistake an ARCH process as a bilinear process if conditional homoscedasticity is assumed. As is well known (e.g. Diebold and Nason (1990), Meese and Rose (1991), Granger (1992, Section 8)), the distinction between nonlinearities in mean and in higher order moments has important economic implications. For example, suppose an asset return follows a bilinear process. Then the level of asset return is predictable using its past history. In contrast, if the asset return follows an ARCH process, then its level is not predictable because it is a martingale difference sequence (m.d.s.). As an important feature, our tests for conditional mean models are robust to conditional heteroscedasticity and all other higher order conditional moments of unknown form. Most existing tests for linearity in mean assume conditional homoscedasticity or i.i.d. errors (e.g. Keenan (1985), Tsay (1986), White (1989), Hamilton (2001), Dahl and Gonzalez-Rivera (2003)).

Section 2 introduces the hypotheses of interest and discusses the concept of (non)linearity in mean. Section 3 describes our approach and introduces our test statistics. Section 4 derives the asymptotic distribution of the tests, and Section 5 investigates their asymptotic power. Section 6 justifies the use of a data-driven lag order and considers a plug-in method. In Section 7, we examine the finite sample performance of the tests. In Section 8, we apply the tests to S&P 500 and NASDAQ daily indices. Section 9 concludes, and all proofs are collected in the Appendix. The GAUSS code for implementing our tests is available from the authors upon request. Throughout, we use $C$ to denote a generic bounded constant, $\| \cdot \|$ the Euclidean norm, and $A^*$ the complex conjugate of $A$.

2. FRAMEWORK AND NONLINEARITY IN MEAN

Suppose $\{Y_t\}$ is a strictly stationary process. We consider a time series model

$$Y_t = g(I_{t-1}, \theta) + \varepsilon_t, \quad t = 1, 2, \ldots, \quad (2.1)$$

where $I_{t-1}$ is an information set at time $t - 1$, which may contain lagged dependent variables $\{Y_{t-j}, j > 0\}$, lagged shocks $\{\varepsilon_{t-j}, j > 0\}$, and current and lagged exogenous variables $\{Z_{t-j}, j \geq 0\}$; $g(I_{t-1}, \theta)$ is a parametric model for $E(Y_t \mid I_{t-1})$, the conditional mean of $Y_t$ given $I_{t-1}$, and $\theta \in \Theta$ is a finite-dimensional parameter. In time series modelling, $I_{t-1}$ is possibly infinite-dimensional (i.e. dating back to the infinite past), as is the case for non-Markovian processes. This poses a challenge in testing adequacy of the model $g(I_{t-1}, \theta)$, due to the curse of dimensionality.

We say that the model $g(I_{t-1}, \theta)$ is correctly specified for $E(Y_t \mid I_{t-1})$ if there is some $\theta_0 \in \Theta$ such that

$$\mathbb{H}_0 : \Pr[g(I_{t-1}, \theta_0) = E(Y_t \mid I_{t-1})] = 1. \quad (2.2)$$

Alternatively, the model $g(I_{t-1}, \theta)$ is misspecified for $E(Y_t \mid I_{t-1})$ if for all $\theta \in \Theta$, we have

$$\mathbb{H}_A : \Pr[g(I_{t-1}, \theta) = E(Y_t \mid I_{t-1})] < 1. \quad (2.3)$$

Conditional mean modelling has been the primary interest in time series analysis, because $E(Y_t \mid I_{t-1})$ is the optimal predictor for $Y_t$ using $I_{t-1}$ in terms of the mean squared error criterion. In addition, as discussed earlier, most economic theories have implications on and only on the conditional mean dynamics of the underlying economic variable.

In time series analysis, testing linearity in mean has attracted much attention, which is often the first stage in nonlinear time series modelling (Granger and Teräsvirta (1993, Chapter 6),
Hansen (1999)). Suppose

\[ g(I_{t-1}, \theta) = X_t' \Lambda(\theta), \tag{2.4} \]

where \( X_t \) is a \( d \times 1 \) vector in \( I_{t-1} \), \( \Lambda(\theta) \) is a \( d \times 1 \) parameter that depends on \( \theta \), and integer \( d \) can be finite or infinite. Following Granger and Teräsvirta (1993) and Lee, White and Granger (1993), we say that \( Y_t \) is linear in mean on \( X_t \) if there exists some \( \theta_0 \in \Theta \) such that

\[ \Pr[E(Y_t \mid I_{t-1}) = X_t' \Lambda(\theta_0)] = 1. \tag{2.5} \]

Otherwise, we say that model (2.4) suffers from neglected nonlinearity in mean. A more restrictive version of this definition was given in Granger and Teräsvirta (1993) and Lee et al. (1993), who consider the case that \( X_t \) is observable with a fixed dimension. Here, we allow \( X_t \) to be unobservable, possibly with an infinite dimension. This generalization is useful because, when \( X_t \) has a fixed dimension, the violation of (2.5) can be caused by neglected higher order lags rather than neglected nonlinearity. In other words, the alternative to (2.4) can be a linear time series with a higher order lag structure.

Our definition of linearity in mean differs from the usual notion of a linear time series in the literature, which is a weighted sum of current and past shocks \( \{\varepsilon_{t-j}, j \geq 0\} \), where \( \{\varepsilon_t\} \) is serially uncorrelated (e.g. Priestley, 1981, p. 141). Such a process may not be linear in mean in the sense of (2.5), because a white noise \( \{\varepsilon_t\} \) may not be a m.d.s. A white noise process with nonzero conditional mean is predictable in mean. Only when \( \{\varepsilon_t\} \) is a m.d.s., the notion of a linear time series coincides with our definition of linearity in mean. The latter concept is more useful for modelling conditional mean dynamics.

Likewise, our concept of nonlinearity in mean differs from the conventional notion of a nonlinear time series. The latter means any departure from a linear time series with independent and identically distributed (i.i.d.) errors \( \{\varepsilon_t\} \). According to this definition, an AR model with ARCH errors is a nonlinear time series. It is linear in mean, however, in view of (2.5). As we have emphasized, it is important to distinguish nonlinearities in different moments, which have different economic implications.

It should be noted that some popular “linearity” tests in the time series literature are designed to check departures from i.i.d. for observed raw data or the model error \( \{\varepsilon_t\} \) (see Barnett, Gallant, Hinich, Jungelges, Kaplan and Jensen, 1997, for a survey). They can capture nonlinearities in mean and in higher order moments, and therefore are not suitable for testing linearity in mean. For example, as pointed out in Lee et al. (1993), the well-known BDS test (Brock et al. (1991), Brock, Dechert, Scheinkman and LeBaron (1996)) can reject a correct linear AR model with ARCH errors. Similarly, the tests by Subba Rao and Gabr (1980) and Hinich (1982) are also not suitable for testing nonlinearity in mean. These tests exploit the bispectral shape of a linear process with i.i.d. errors and can detect nonlinearity in mean and in higher order moments.3

Existing parametric tests for linearity in mean are powerful against some misspecifications in mean, but they all suffer from power loss in detecting certain nonlinear alternatives (e.g. Tong, 1990, Chapter 5). When there is no prior information about the alternative, it is desirable to have an omnibus test against a wide range of alternatives. Tsay (2001, p. 268) suggested combining several procedures via an augmented alternative. This will ensure power against a wider range of alternatives than an individual test, but the choice of the augmented alternative is somewhat arbitrary. Another approach is to estimate \( E(Y_t \mid I_{t-1}) \) nonparametrically and compare the nonparametric estimator with \( g(I_{t-1}, \theta) \), or equivalently, to estimate \( E(\varepsilon_t \mid I_{t-1}) \) nonparametrically and check if it is zero (Li (1999), Gao and King (2001)). This approach works

3. Although the generalized spectrum shares certain features similar to the bispectrum, our generalized spectral derivative introduced below focuses on and only on serial dependence in mean. Thus, it is suitable for testing conditional mean specification.
when \(E(Y_t \mid I_{t-1}) = E(Y_t \mid X_t)\) a.s. and the dimension of \(X_t \in I_{t-1}\) is small. However, it is not expected to work well in finite samples when the dimension of \(X_t\) is large. Our generalized spectral approach provides a solution to this difficulty of “curse of dimensionality". It checks many lags in a pairwise manner, which avoids the “curse of dimensionality".\(^4\) This is similar in spirit to the nonparametric additive time series modelling strategy in the literature (e.g. Marsry and Tjøstheim (1997), Gao, Tong and Wolff (2002), Kim and Linton (2003)). On the other hand, the generalized spectral derivative can detect various misspecified functional forms at any given lag order. One can view our procedures, when applied to linearity testing, as checking the joint hypotheses of (i) \(E(Y_t \mid I_{t-1}) = E(Y_t \mid X_t)\) for some \(X_t \in I_{t-1}\) and (ii) \(E(Y_t \mid X_t) = X_t^j\theta_0\) for some \(\theta_0\). All existing tests for linearity in mean only focus on testing (ii) and ignore testing (i); they can easily miss conditional mean misspecifications that occur at higher lag orders. Moreover, even for any given lag order, the existing linearity tests except White’s (1989) neural network test cannot detect all departures from (i).

3. APPROACH AND TEST STATISTICS

3.1. Generalized spectral analysis

Our approach to testing correct conditional mean specification (\(\mathbb{H}_0\) in (2.2)) is based on Hong’s (1999) generalized spectrum, which is an analytic tool for nonlinear time series, just as the power spectrum is an analytic tool for linear time series (Priestley, 1981).

Recall the model error
\[
e_t(\theta) \equiv Y_t - g(I_{t-1}, \theta)
\]
has the property that \(E[\varepsilon_t(\theta_0) \mid I_{t-1}] = 0\) a.s. for some \(\theta_0 \in \Theta\). This implies
\[
E[\varepsilon_t(\theta_0) \mid I_{t-1}^k] = 0 \quad \text{a.s.,}
\]
where \(I_{t-1}^k \equiv \{\varepsilon_{t-1}(\theta_0), \varepsilon_{t-2}(\theta_0), \ldots\}\). Thus, to test \(\mathbb{H}_0\), we can check if \(E[\varepsilon_t(\theta_0) \mid I_{t-1}^k] = 0\) a.s.\(^5\) Still, we have the curse of dimensionality problem because \(I_{t-1}^k\) has an infinite dimension. Fortunately, the generalized spectral approach provides a sensible way to tackle this difficulty.

For notational economy, we put \(\varepsilon_t \equiv \varepsilon_t(\theta)\). Suppose \(\{\varepsilon_t\}\) is a strictly stationary process with marginal characteristic function \(\varphi(u) \equiv E(e^{iu\varepsilon_t})\) and pairwise joint characteristic function \(\varphi_i(u, v) \equiv E(e^{iu\varepsilon_t + iv\varepsilon_{t-j}})\), where \(i = \sqrt{-1}, u, v \in \mathbb{R}\), and \(j = 0, \pm 1, \ldots\). The basic idea of the generalized spectrum is to consider the spectrum of the transformed series \(e^{iu\varepsilon_t}\). It is defined as
\[
f(\omega, u, v) \equiv \frac{1}{2\pi} \sum_{j=-\infty}^{\infty} \sigma_j(u, v)e^{-ij\omega}, \quad \omega \in [-\pi, \pi],
\]
where \(\omega\) is the frequency, and \(\sigma_j(u, v)\) is the covariance function of the transformed series:
\[
\sigma_j(u, v) \equiv \text{cov}(e^{iu\varepsilon_t}, e^{iv\varepsilon_{t-j}}), \quad j = 0, \pm 1, \ldots
\]
The function \(f(\omega, u, v)\) can capture any type of pairwise serial dependence in \(\{\varepsilon_t\}\), i.e. dependence between \(\varepsilon_t\) and \(\varepsilon_{t-j}\) for any nonzero lag \(j\), including that with zero autocorrelation. This is analogous to the higher order spectra (Brillinger and Rosenblatt, 1967a,b) in the sense that \(f(\omega, u, v)\) can capture the serial dependence in higher order moments. However, unlike

\(^4\) From a theoretical point of view, the pairwise approach will miss dependent processes that are pairwise independent. However, such processes apparently do not appear in most empirical applications in economics and finance.

\(^5\) For a univariate time series, the knowledge of \(I_{t-1} = \{Y_{t-1}, Y_{t-2}, \ldots\}\) is equivalent to the knowledge of \(I_{t-1}^k = \{\varepsilon_{t-1}(\theta_0), \varepsilon_{t-2}(\theta_0), \ldots\}\) under certain regularity conditions (e.g. Priestley, 1988, p. 72). However, when \(I_{t-1}\) contains other current and lagged exogenous variables, these two information sets generally differ. Below, we will first develop tests based on \(I_{t-1}^k\), and then consider extensions to the more general information set in Section 5.
the higher order spectra, \( f(\omega, u, v) \) does not require existence of any moment of \( \{\varepsilon_t\} \). This is important in economics and finance because it has been argued that the higher order moments of many financial time series may not exist.

When \( \sigma^2 \equiv E(\varepsilon_t^2) \) exists, we can obtain the power spectrum as a derivative of \( f(\omega, u, v) \):

\[
-\frac{\partial^2}{\partial u \partial v} f(\omega, u, v) \Big|_{(u,v)=(0,0)} = h(\omega) \equiv \frac{1}{2\pi} \sum_{j=-\infty}^{\infty} \text{cov}(\varepsilon_t, \varepsilon_{t-j}) e^{-ij\omega}, \quad \omega \in [-\pi, \pi].
\]

For this reason, we call \( f(\omega, u, v) \) the generalized spectrum of \( \{\varepsilon_t\} \).

As is well known, the interpretation of spectral analysis is much more difficult for nonlinear time series than for linear time series. For example, the bispectrum has no physical \( (e.g. \) energy decomposition over frequencies) interpretation, unlike the power spectrum \( h(\omega) \). This is also the case for the generalized spectrum \( f(\omega, u, v) \). However, the basic idea of characterizing cyclical dynamics still applies: \( f(\omega, u, v) \) has useful interpretations when searching for linear or nonlinear cycles. A strong cyclicity of data may be linked with a strong serial dependence in \( \{\varepsilon_t\} \) that may not be captured by the autocorrelation function. The generalized spectrum \( f(\omega, u, v) \) can capture such nonlinear cyclical patterns by displaying distinct spectral peaks. For example, suppose an asset return series has a stochastic cyclical dynamics in volatility, which may be linked to business cycles \( (e.g. \) Hamilton and Lin, 1996). Then the power spectrum \( h(\omega) \) will be flat and miss the volatility cycles. In contrast, \( f(\omega, u, v) \) can effectively capture such cycles. More generally, the generalized spectrum can capture cyclical dynamics caused by linear and nonlinear dependence. The latter includes the serial dependence in volatility, skewness and other higher order conditional moments. \(^6\)

The generalized spectrum \( f(\omega, u, v) \) itself is not suitable for testing \( \mathcal{H}_0 \) in (2.2), because it can capture the serial dependence in mean and in higher order moments. An example is an ARCH process. The generalized spectrum \( f(\omega, u, v) \) can capture this process, although it is a m.d.s. However, just as the characteristic function can be differentiated to generate various moments of \( \{\varepsilon_t\} \), \( f(\omega, u, v) \) can be differentiated to capture the serial dependence in various moments. To capture (and only capture) the serial dependence in the conditional mean, one can use the derivative

\[
f^{(0,1,0)}(\omega, 0, v) \equiv \frac{1}{2\pi} \sum_{j=-\infty}^{\infty} \sigma_j^{(1,0)}(0, v) e^{-ij\omega}, \quad \omega \in [-\pi, \pi], \tag{3.4}
\]

where

\[
\sigma_j^{(1,0)}(0, v) \equiv \frac{\partial}{\partial u} \sigma_j(u, v) \Big|_{u=0} = \text{cov}(i\varepsilon_t, e^{i\varepsilon_{t-j}}).
\]

The measure \( \sigma_j^{(1,0)}(0, v) \) checks whether the autoregression function \( E(\varepsilon_t \mid \varepsilon_{t-j}) \) at lag \( j \) is zero. Under appropriate conditions, \( \sigma_j^{(1,0)}(0, v) = 0 \) for all \( v \in \mathbb{R} \) if and only if \( E(\varepsilon_t \mid \varepsilon_{t-j}) = 0 \) a.s. \(^7\) The autoregression function can capture linear and nonlinear serial dependence in mean, including the processes with zero autocorrelation. Examples are a bilinear autoregressive process \( \varepsilon_t = \alpha z_{t-1} \varepsilon_{t-2} + z_t \) and a nonlinear moving-average process \( \varepsilon_t = \alpha z_{t-1} z_{t-2} + z_t \), where \( \{z_t\} \sim \text{i.i.d.} (0, \sigma^2) \). These processes are white noises, but they are not a m.d.s., because their conditional means are time-varying. Thus, \( E(\varepsilon_t \mid \varepsilon_{t-j}) \) is a natural tool to test \( \mathcal{H}_0 \), whereas \( \text{cov}(\varepsilon_t, \varepsilon_{t-j}) \) will miss such subtle nonlinear processes. Nevertheless, \( E(\varepsilon_t \mid \varepsilon_{t-j}) \) has not been

\(^6\) A potentially useful application is the investigation of possible nonlinear business cycles by \( f(\omega, u, v) \). The power spectrum \( h(\omega) \), when applied to macroeconomic time series such as the U.S. GDP growth rates, often produces a flat spectrum. However, some nonlinear time series experts \( (e.g. \) Tong, 1990, p. 232) believe that business cycles are related to nonlinear cyclical dynamics. It will be interesting to examine whether \( f(\omega, u, v) \) can capture and identify such nonlinear cycles.

\(^7\) See Bierens (1982) and Stinchcombe and White (1998) for discussion in a different context with i.i.d. samples.
as widely used as cov(\(e_t, e_{t-j}\)). An exception is Hjellvik and Tjøstheim (1996), who considered testing linearity in mean for observed raw data using a kernel estimator for the autoregression function. Tong (1990) and Teräsvirta et al. (1994a) also discussed smoothed nonparametric estimation of the autoregression function.

Although \(E(e_t \mid e_{t-j})\) and \(\sigma_j^{(1,0)}(0, v)\) are equivalent measures, the use of \(\sigma_j^{(1,0)}(0, v)\) avoids smoothed nonparametric estimation. In addition, the measure \(\sup_{v \in \mathbb{R}} |\sigma_j^{(1,0)}(0, v)|\) can be viewed as an operational version of the maximum mean correlation, \(\max_{f(.)} |\text{corr}[e_t, f(e_{t-j})]|\), which was proposed by Granger and Teräsvirta (1993, p. 23) as a measure for nonlinearity in mean. Similarly, the supremum generalized spectral derivative modulus

\[
m(\omega) = \sup_{v \in (-\infty, \infty)} |f^{(0,1,0)}(\omega, 0, v)|,
\]

can be viewed as the maximum dependence in mean at frequency \(\omega\). It can be used to search cycles in mean that are caused by linear or nonlinear serial dependence in mean. An example of the latter is the well-knownARCH-in-mean effect (Engle, Lilien and Robins, 1987).

The hypothesis of \(E(e_t \mid I_{t-1}^e) = 0\ a.s.\) is not the same as the hypothesis of \(E(e_t \mid e_{t-j}) = 0\ a.s.\) for all \(j > 0\). The former implies the latter but not vice versa. This is the price we have to pay for dealing with the difficulty of the “curse of dimensionality”. One example that is not a m.d.s. but has \(E(e_t \mid e_{t-j}) = 0\ a.s.\) for all \(j > 0\) is a nonlinear moving-average process

\[
e_t = \alpha z_{t-2} z_{t-3} + z_t,
\]

\(\{z_t\} \sim \text{i.i.d.} (0, \sigma^2)\).

Obviously, there are many such examples.

It is rather difficult to formally characterize the gap between \(E(e_t \mid I_{t-1}^e) = 0\ a.s.\) and \(E(e_t \mid e_{t-j}) = 0\ a.s.\) for all \(j > 0\). However, these two hypotheses coincide under some special but important cases. The first case is when \(\{e_t\}\) is a stationary Gaussian process, which can be a long memory. The second case is when \(\{e_t\}\) is a Markovian process. This covers both linear and nonlinear Markovian processes. The examples of the latter are a nonlinear autoregressive process \(e_t = g(e_{t-1}) + z_t\) and a bilinear autoregressive process \(e_t = \alpha e_{t-1} + \beta z_t e_{t-1} + z_t\), where \(\{z_t\} \sim \text{i.i.d.} (0, \sigma^2)\).

The third case is when \(\{e_t\}\) follows an additive-in-mean process:

\[
e_t = \alpha_0 + \sum_{j=1}^{\infty} g_j(e_{t-j}) + h_{j/2} z_t,
\]

where \(g_j(.)\) is not a zero function at least for some lag \(j > 0\), and \(h_{j/2} \equiv h(I_{t-1}^e)\) may not be additive. Additive time series processes have attracted considerable interest in the nonparametric literature (e.g. Marsys and Tjøstheim (1997), Gao et al. (2002), Kim and Linton (2003)).

To reduce the gap between \(E(e_t \mid I_{t-1}^e) = 0\ a.s.\) and \(E(e_t \mid e_{t-j}) = 0\ a.s.\) for all \(j > 0\), we can extend \(f^{(0,1,0)}(\omega, 0, v)\) to a generalized bispectral derivative

\[
\frac{\partial}{\partial u} B(\omega_1, \omega_2, u, v_1, v_2) \bigg|_{u=0} = \frac{1}{(2\pi)^2} \sum_{j=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} \sigma_j^{(1,0,0)}(0, v_1, v_2) e^{-ij\omega_1 - il\omega_2},
\]

where

\[
\sigma_j^{(1,0,0)}(0, v_1, v_2) \equiv \frac{\partial}{\partial u} \sigma_{j,0}(0, v_1, v_2) \bigg|_{u=0} = E[i e_t \{e^{iv_1 e_{t-1-j}} - \varphi(v_1)} e^{iv_2 e_{t-1-l}} - \varphi(v_2)\}]
\]

and \(\sigma_{j,i}(u, v_1, v_2) \equiv E[(e^{iu} - \varphi(u)} e^{iv_1 e_{t-1-j}} - \varphi(v_1)} e^{iv_2 e_{t-1-l}} - \varphi(v_2)\])\) is a generalized third order cumulant. This is equivalent to the use of \(E(e_t \mid e_{t-j}, e_{t-l})\), which was suggested

8. We thank Hidehiko Ichimura for providing this nice example which the generalized spectral derivative \(f^{(0,1,0)}(\omega, 0, v)\) will miss.

9. It is well known (e.g. Granger and Teräsvirta, 1993, pp. 17, 44) that the class of nonlinear moving averages processes is generally not invertible, and as a consequence, has found little empirical application in practice.
by Tong (1990, p. 219). With $\sigma_{j,l}^{(1,0,0)}(0, v_1, v_2)$, we can detect a larger class of alternatives to $E(\varepsilon_t | I^k_{t-1}) = 0$ a.s.$^{10}$ For example, it can easily detect the nonlinear moving-average process (3.6). Note that the nonparametric generalized bispectral derivative approach can check many pairs of lags $(k, l)$, while still avoiding the curse of dimensionality. Nevertheless, in this paper, we focus on $\sigma_{j,l}^{(1,0,0)}(0, v)$ for simplicity.

3.2. Generalized spectral derivative estimation

In the present context, $\varepsilon_t$ is not observed. Suppose we have a random sample $\{Y_t\}_{t=1}^T$ which is used to estimate model $g(I_{t-1}, \theta)$. We then obtain the estimated model residual

$$\hat{\varepsilon}_t \equiv Y_t - g(I^k_{t-1}, \hat{\theta}), \quad t = 1, \ldots, T,$$

where $I^k_{t-1}$ is the information set observed at time $t - 1$, and $\hat{\theta}$ is a $\sqrt{T}$-consistent estimator for $\theta_0$. Examples of $\hat{\theta}$ are conditional least squares and quasi-maximum likelihood estimators.

We can estimate $f^{(0,1,0)}(\omega, 0, v)$ by a smoothed kernel estimator

$$\hat{f}^{(0,1,0)}(\omega, 0, v) \equiv \frac{1}{2\pi} \sum_{j=-1}^{T/2} (1 - |j/T|)^{1/2} k(j/p) \hat{\sigma}_j^{(1,0)}(0, v)e^{-ij\omega}, \quad \omega \in [-\pi, \pi],$$

where $\hat{\sigma}_j^{(1,0)}(0, v) = \frac{d}{dv} \hat{\sigma}_j(u, v)|_{u=0}$, $\hat{\sigma}_j(u, v) = \hat{\phi}_j(u, v) - \hat{\phi}_j(u, 0)\hat{\phi}_j(0, v)$, and

$$\hat{\phi}_j(u, v) = \frac{1}{T - |j|} \sum_{t=|j|+1}^{T} e^{iu\hat{\varepsilon}_t + iv\hat{\varepsilon}_{t-1}}.$$

Here, $p \equiv p(T)$ is a bandwidth, and $k : \mathbb{R} \to [-1, 1]$ is a symmetric kernel. Examples of $k(\cdot)$ include the Bartlett, Danielli, Parzen and Quadratic spectral kernels (e.g. Priestley, 1981, p. 442). The factor $(1 - |j/T|)^{1/2}$ is a finite-sample correction. It could be replaced by unity. Under certain conditions, $\hat{f}^{(0,1,0)}(\omega, 0, v)$ is consistent for $f^{(0,1,0)}(\omega, 0, v)$. See Theorem 2 below.

Under $H_0$, the generalized spectral derivative $f^{(0,1,0)}(\omega, 0, v)$ becomes a “flat” spectrum:

$$f^{(0,1,0)}_0(\omega, 0, v) = \frac{1}{2\pi} \sigma_0^{(1,0)}(0, v), \quad \omega \in [-\pi, \pi],$$

which can be consistently estimated by

$$\hat{f}^{(0,1,0)}_0(\omega, 0, v) \equiv \frac{1}{2\pi} \hat{\sigma}_0^{(1,0)}(0, v), \quad \omega \in [-\pi, \pi].$$

To test $H_0$, we can compare $\hat{f}^{(0,1,0)}(\omega, 0, v)$ with $f^{(0,1,0)}_0(\omega, 0, v)$.

3.3. Tests under conditional heteroscedasticity

There is a growing consensus among economists that the volatilities of most high-frequency economic and financial data are time-varying. It is well known that the asymptotic variances of test statistics for autocorrelations and conditional mean models depend on the type and degree of heteroscedasticity present. Ignoring it will invalidate the limit distributions of test statistics (e.g. Diebold (1986), Lo and MacKinlay (1988), Wooldridge (1990), Whang (1998)). This is also true for our tests. In fact, for our tests, it is also important to take into account other higher order time-varying moments. Some recent studies (e.g. Gallant, Hsieh and Tauchen (1991),

10. Tsay (1986), Hsieh (1989) and Hinich and Patterson (1993) used the third order cumulant $E(\varepsilon_t \varepsilon_{t-j} \varepsilon_{t-l})$ to detect nonlinearity in mean. The measure $\sigma_{j,l}(u, v_1, v_2)$ can detect a wider class of processes than $E(\varepsilon_t \varepsilon_{t-j} \varepsilon_{t-l})$. 

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Hansen (1994), Harvey and Siddique (1999, 2000), Jondeau and Rockinger (2003) documented time-varying conditional skewness and kurtosis of asset returns. Below, we first propose a test of $H_0$ that is robust to conditional heteroscedasticity and other time-varying higher order moments of unknown form. This is one of the most important contributions of our paper in terms of empirical relevance and asymptotic analysis. The asymptotic analysis is nontrivial because of the need to take care of the serial dependence in higher order moments.

Our test statistic that is robust to conditional heteroscedasticity and other time-varying higher order conditional moments of unknown form is given as follows:

$$
\hat{M}_1(p) = \left[ \sum_{j=1}^{T-1} k^2(j/p)(T - j) \int |\hat{\sigma}^{(1,0)}_j(0, v)|^2 dW(v) - \hat{C}_1(p) \right] / \sqrt{\hat{D}_1(p)}, \quad (3.11)
$$

where $W : \mathbb{R} \rightarrow \mathbb{R}^+$ is a nondecreasing function that weighs sets symmetric about zero equally,

$$
\hat{C}_1(p) = \sum_{j=1}^{T-1} k^2(j/p) \frac{1}{T-j} \sum_{t=j}^{T-1} \hat{\varepsilon}_t^2 \int |\hat{\psi}_{t-j}(v)|^2 dW(v),
$$

$$
\hat{D}_1(p) = 2 \sum_{j=1}^{T-2} \sum_{l=1}^{T-2} k^2(j/p) k^2(l/p) \int \int \frac{1}{T - \max(j, l)} \times \sum_{t=\max(j, l)+1}^{T} \hat{\varepsilon}_t^2 \hat{\psi}_{t-j}(v) \hat{\psi}_{t-l}(v')^2 dW(v) dW(v'),
$$

and $\hat{\psi}(v) = e^{iv\hat{\nu}_t} - \hat{\phi}(v)$, and $\hat{\phi}(v) = T^{-1} \sum_{t=1}^{T} e^{iv\hat{\nu}_t}$. Throughout, all unspecified integrals are taken on the support of $W(\cdot)$. An example of $W(\cdot)$ is the $N(0, 1)$ CDF, which is commonly used in the characteristic function literature. The factors $\hat{C}_1(p)$ and $\hat{D}_1(p)$ are approximately the mean and the variance of $T \int \int \hat{f}^{(0,1,0)}(\omega, 0, v) - \int \hat{f}^{(0,1,0)}(\omega, 0, v)^2 d\omega dW(v)$. They have taken into account the impact of conditional heteroscedasticity and other time-varying higher order conditional moments.

### 3.4. Tests under conditional homoscedasticity

To examine why it is important to take into account the impact of conditional heteroscedasticity and higher order time-varying moments in testing $H_0$, we now derive the generalized spectral tests for $H_0$ under conditional homoscedasticity and under i.i.d. for $\{\varepsilon_t\}$, respectively. Suppose $\{\varepsilon_t\}$ is conditionally homoscedastic (i.e. $E(\varepsilon_t^2 | I_{t-1}) = \sigma^2$ a.s.). Then we can simplify our test statistic as follows:

$$
\hat{M}_2(p) = \left[ \sum_{j=1}^{T-1} k^2(j/p)(T - j) \int |\hat{\sigma}^{(1,0)}_j(0, v)|^2 dW(v) - \hat{C}_2(p) \right] / \sqrt{\hat{D}_2(p)}, \quad (3.12)
$$

where

$$
\hat{C}_2(p) = \hat{\sigma}_0^2 \int \sigma_0(v, -v) dW(v) \sum_{j=1}^{T-1} k^2(j/p),
$$

$$
\hat{D}_2(p) = 2\hat{\sigma}_0^4 \sum_{j=1}^{T-2} \sum_{l=1}^{T-2} k^2(j/p) k^2(l/p) \int \int |\hat{\sigma}_{j-l}(v, v')|^2 dW(v) dW(v'),
$$

and $\hat{\sigma}_0^2 = \sum_{t=1}^{T-1} \hat{\varepsilon}_t^2$ is the sample variance of $\{\varepsilon_t\}_{t=1}^{T}$. Both the centring and scale factors $\hat{C}_2(p)$ and $\hat{D}_2(p)$ have been simplified, by exploiting the implication of conditional homoscedasticity. The form of $\hat{D}_2(p)$ still takes into account the impact of possibly time-varying third order and higher order moments.
3.5. Tests under the i.i.d. case

Many existing tests for linearity assume i.i.d. for \( \{\varepsilon_t\} \) under \( \mathbb{H}_0 \); some of them further assume i.i.d. \( N(0, \sigma^2) \). When \( \{\varepsilon_t\} \) is i.i.d. \( (0, \sigma^2) \), which implies \( \mathbb{H}_0 \), our test statistic can be further simplified:

\[
\hat{M}_3(p) = \left[ \sum_{j=1}^{T-1} k^2(j/p)(T - j) \int |\hat{\sigma}_j^{(1,0)}(0, v)|^2 dW(v) - \hat{C}_3(p) \right] / \sqrt{\hat{D}_3(p)},
\]

(3.13)

where \( \hat{C}_3(p) = \hat{C}_2(p) \) and \( \hat{D}_3(p) = 2\hat{\sigma}^4 \int \int |\hat{\sigma}_0(v, v')|^2 dW(v)dW(v') \sum_{j=1}^{T-1} k^4(j/p) \).

The scale factor \( \hat{D}_3(p) \) has been greatly simplified. Interestingly, the \( M_3(p) \) test derived under conditional homoscedasticity differs from the \( M_3(p) \) test derived under i.i.d. This is because \( M_2(p) \) still takes into account possibly time-varying higher order moments (e.g. skewness and kurtosis). We note the fact that the limit distribution of \( M_3(p) \) test is valid when \( \{\varepsilon_t\} \) is i.i.d. does not mean that \( M_3(p) \) is an omnibus test for i.i.d., because it only checks the serial dependence in mean. To test i.i.d. for \( \{\varepsilon_t\} \), the BDS test or Hong and Lee’s (2003) test will be suitable. Nevertheless, these i.i.d. tests are not suitable for testing conditional mean specification, because they check the serial dependence in every moment.

4. ASYMPTOTIC DISTRIBUTION

To derive the null limit distribution of our tests, we provide some regularity conditions:

**Assumption A1.** \( \{Y_t\} \) is a strictly stationary time series process such that \( \mu_t \equiv E(Y_t \mid I_{t-1}) \) exists a.s., where \( I_{t-1} \) is an information set at time \( t - 1 \) that may contain lagged dependent variables \( \{Y_{t-j} \mid j > 0\} \), lagged shocks \( \{\varepsilon_{t-j} \equiv Y_{t-j} - \mu_t, j > 0\} \), as well as current and lagged exogenous variables \( \{Z_{t-j} \mid j \geq 0\} \), with \( E(\varepsilon_t^4) \leq C \).

**Assumption A2.** For each sufficiently large integer \( q \), there exists a strictly stationary process \( \{\varepsilon_{q,t}\} \) measurable with respect to the sigma field generated by \( \{\varepsilon_{t-1}, \varepsilon_{t-2}, \ldots, \varepsilon_{t-q}\} \) such that as \( q \to \infty, \varepsilon_{q,t} \) is independent of \( \{\varepsilon_{t-q-1}, \varepsilon_{t-q-2}, \ldots\} \) for each \( t \), \( E(\varepsilon_{q,t} \mid I_{t-1}) = 0 \) a.s., \( E(\varepsilon_{t} - \varepsilon_{q,t})^2 \leq Cq^{-\kappa} \) for some constant \( \kappa \geq 1 \), and \( E(\varepsilon_{q,t}^4) \leq C \) for all large \( q \).

**Assumption A3.** \( g(I_{t-1}, \theta) \) is a parametric model for \( \mu_t \), where \( \theta \in \Theta \) is a finite-dimensional parameter, such that (a) \( g(\cdot, \theta) \) is measurable with respect to \( I_{t-1} \) for each \( \theta \in \Theta \), and (b) with probability one, \( g(I_{t-1}, \cdot) \) is continuously twice differentiable with respect to \( \theta \in \Theta \), and \( E_{\sup_{\theta \in \Theta}} \| \frac{\partial}{\partial \theta} g(I_{t-1}, \theta) \|^2 \leq C \) and \( E_{\sup_{\theta \in \Theta}} \| \frac{\partial^2}{\partial \theta^2} g(I_{t-1}, \theta) \|^2 \leq C \).

**Assumption A4.** \( \hat{\theta} - \theta_0 = O_P(T^{-1/2}) \), where \( \theta_0 \equiv p \lim(\hat{\theta}) \in \Theta \).

**Assumption A5.** Let \( I_{t+} \) be an observed information set available at time \( t \) that may contain some assumed initial values. Then \( \lim_{T \to \infty} \sum_{t=1}^{T} [E_{\sup_{\theta \in \Theta}} |g(I_{t-1}, \theta) - g(I_{t-1}, \theta)|^4]^{1/4} \leq C \).

**Assumption A6.** \( k : \mathbb{R} \to [-1, 1] \) is symmetric about 0, and is continuous at 0 and all points except a finite number of points, with \( k(0) = 1 \) and \( |k(z)| \leq C|z|^{-b} \) as \( z \to \infty \) for some \( b > 1 \).

**Assumption A7.** \( W : \mathbb{R} \to \mathbb{R}^+ \) is nondecreasing and weighs sets symmetric about zero equally, with \( \int v^4 dW(v) \leq C \).
Assumption A8. Put \( \psi_t(v) \equiv e^{iv\epsilon_t} - \varphi(v) \) and \( \sigma^2 \equiv E(\epsilon_t^2). \) Then \( \{ \frac{\partial}{\partial \theta} g(I_t, \theta_0), \epsilon_t \} \) is a strictly stationary process such that (a) \( \sum_{j=1}^{\infty} ||\text{cov}[\frac{\partial}{\partial \theta} g(I_t, \theta_0), \frac{\partial}{\partial \theta} g(I_{t-j}, \theta_0)]|| \leq C; \) (b) \( \sum_{j=1}^{\infty} \sup_{(u,v) \in \mathbb{R}^2} |\sigma_j(u,v)| \leq C; \) (c) \( \sum_{j=1}^{\infty} \sup_{v \in \mathbb{R}} ||\text{cov}[\frac{\partial}{\partial \theta} g(I_t, \theta_0), \psi_{t-j}(v)]|| \leq C; \) (d) \( \sum_{j=1}^{\infty} \sup_{(u,v) \in \mathbb{R}^2} |E(\epsilon_t^2 - \sigma^2 \psi_{t-j}(u) \psi_{t-j}(v))| \leq C; \) (e) \( \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} \sum_{t=-\infty}^{\infty} \sup_{v \in \mathbb{R}} \| \epsilon_{j,t} r,v \| \leq C, \) where \( \kappa_{j,t} r,v \) is the fourth order cumulant of the joint distribution of the process \( \{ \frac{\partial}{\partial \theta} g(I_t, \theta_0), \psi_{t-j}(v), \frac{\partial}{\partial \theta} g(I_{t-1}, \theta_0), \psi_{t-1}(v) \} \).

Assumptions A1 and A2 are regularity conditions on the data generating process (DGP). We impose strict stationarity on \( \{ Y_t \} \). The existence of the conditional mean \( \mu_t \) can be ensured by assuming \( E(Y_t^2) < \infty \). Assumption A2 is required only under \( \mathbb{Z}_0 \). It assumes that the m.d.s. \( \{ \epsilon_t \} \) can be approximated by a \( q \)-dependent m.d.s. process \( \{ \eta_t \} \) arbitrarily well when \( q \) is sufficiently large. Horowitz (2003) imposed a similar condition in a different context. Because \( \{ \epsilon_t \} \) is a m.d.s., Assumption A2 essentially imposes restrictions on the serial dependence in higher order moments of \( \epsilon_t \). Among other things, it implies ergodicity for \( \{ \epsilon_t \} \). It holds trivially when \( \{ \epsilon_t \} \) is a \( q \)-dependent process with an arbitrarily large but finite order \( q \). It also covers many non-Markovian processes. To appreciate this, we first consider a threshold GARCH(1, 1) error process \( \{ \epsilon_t \} \):

\[
\begin{align*}
\epsilon_t & = h_t^{1/2} \epsilon_t, \\
h_t & = \gamma + \alpha h_{t-1} + \beta^+ \epsilon_{t-1}^2 (\epsilon_{t-1} > 0) + \beta^- \epsilon_{t-1}^2 (\epsilon_{t-1} \leq 0),
\end{align*}
\]

(4.1)

where \( \mathbb{1}(\cdot) \) is the indicator function. This was proposed by Glosten, Jagannathan and Runkle (1993). It includes standard GARCH(1, 1) processes if \( \beta^+ = \beta^- \). Putting \( \xi_t \equiv \gamma + \beta^+ \epsilon_{t-1}^2 (\epsilon_{t-1} > 0) + \beta^- \epsilon_{t-1}^2 (\epsilon_{t-1} \leq 0) \), we have \( h_t = \gamma + \gamma \sum_{j=1}^{\infty} \prod_{i=1}^{j} \xi_{t-i} \). Define \( \epsilon_{q,t} \equiv h_{q,t}^{1/2} \epsilon_t \), where \( h_{q,t} \equiv \gamma + \gamma \sum_{j=1}^{q} \prod_{i=1}^{j} \xi_{t-i} \). Then

\[
E(\epsilon_{q,t})^2 = E(h_{q,t}^{1/2} - h_{q,t}^{1/2})^2 \leq E(h_t - h_{q,t}) = \gamma \sum_{j=q+1}^{\infty} \prod_{i=1}^{j} E(\xi_{t-i}) = \frac{\gamma \rho^{q+1}}{1-\rho},
\]

with \( \rho \equiv E(\xi_t) = \alpha + \beta^+ + (\beta^- - \beta^+) E(\epsilon_t^2 1(\epsilon_t \leq 0)) \). Thus, Assumption A2 holds if \( \rho < 1 \).

For another example, we consider a general stochastic volatility process for \( \{ \epsilon_t \} \):

\[
\begin{align*}
\epsilon_t & = \exp(\frac{1}{2} h_t) \epsilon_t, \\
h_t & = \alpha_0 + \sum_{j=1}^{\infty} \alpha_j z_{t-j} + \eta_t, \\
\eta_t \sim & \text{ i.i.d.} \ N(0, \sigma^2),
\end{align*}
\]

(4.2)

where \( \sum_{j=1}^{\infty} \alpha_j^2 < \infty \). We do not assume independence between \( \{ z_t \} \) and \( \{ \eta_t \} \). Thus, like (4.1), (4.2) can also capture asymmetry in volatility. Now, put \( \epsilon_{q,t} \equiv \exp(\frac{1}{2} h_{q,t}) \epsilon_t \), where \( h_{q,t} \equiv \alpha_0 + \sum_{j=1}^{q} \alpha_j z_{t-j} + \eta_t \). Then we have

\[
E(\epsilon_{q,t})^2 = E[e^{\frac{1}{2} h_{q,t}} e^{\frac{1}{2} (h_t - h_{q,t})} - 1] z_t \leq \frac{1}{2} [E(e^{2h_{q,t}} (e^{\frac{1}{2} (h_t - h_{q,t})}) - 1^4)]^{\frac{1}{2}} \leq C \sum_{j=q+1}^{\infty} \sigma_j^2
\]

provided \( E(z_t^4) < \infty \), where we have made use of the fact that the \( N(0, \sigma^2) \) moment generating function is \( E(e^{\lambda \eta_t}) = \exp(\frac{1}{2} \sigma^2 \lambda^2) \) for \( \lambda \in \mathbb{R} \) and the inequality that \( |e^{x} - 1| \leq 2|x| \) for small \( x \). Thus, Assumption A2 holds if \( \sum_{j=q+1}^{\infty} \alpha_j^2 \leq C q^\kappa \). A sufficient condition is \( \alpha_j \leq C_j^{-(\kappa+1)} \). This rules out long-memory stochastic volatility processes given \( \kappa \geq 1 \), because \( \sum_{j=-\infty}^{\infty} \text{cov}(h_t, h_{t-j}) = (\sum_{j=1}^{\infty} \alpha_j)^2 < \infty. \)
Assumption A3 is a standard condition on the conditional mean model \( g(I_{t-1}, \theta) \). For a linear model \( g(I_{t-1}, \theta) = X_t' \theta \), where \( X_t \in \mathcal{L}_{t-1} \) is finite-dimensional, it suffices if \( E\|X_t\|^4 \leq C \). Assumption A3 covers many stationary nonlinear time series conditional mean models, such as bilinear autoregressive, exponential autoregressive, nonlinear moving average, Markov regime-switching, smooth transition and Poisson jump models. It also covers threshold autoregression models with known thresholds. An example is the class of self-exciting autoregressive threshold models for the U.S. economy, where recession and expansion are defined as the GDP growth rate being larger or smaller than zero (Tiao and Tsay (1994), Potter (1995)). However, Assumption A3 rules out the autoregressive threshold models with unknown thresholds considered in Hansen (2000), where \( g(I_{t-1}, \theta) \) is not continuous in threshold parameters. We conjecture that our tests are applicable to these models under additional conditions, but we do not attempt to justify this here, as it is beyond the scope of this paper.

Assumption A4 requires a \( \sqrt{T} \)-consistent estimator \( \hat{\theta} \), which may not be asymptotically most efficient. It can be a conditional least squares estimator or a conditional quasi-maximum likelihood estimator. Also, we do not need to know the asymptotic expansion of \( \hat{\theta} \), because the sampling variation in \( \theta \) does not affect the limit distributions of \( \tilde{M}_n(p) \). These features are similar in spirit to Wooldridge’s (1990) heteroscedasticity-robust modified moment-based tests. Assumption A5 is a condition on the truncation of information set \( I_{t-1} \), which usually contains information dating back to the very remote past and so may not be observable. Because of the truncation, one may have to assume some initial values in estimating the model \( g(I_{t-1}, \theta) \); Assumption A5 ensures that the use of initial values, if any, has no impact on the limit distribution of \( \tilde{M}_n(p) \). For instance, consider an ARMA(1, 1) model:

\[
g(I_{t-1}, \theta) = \alpha Y_{t-1} + \beta \varepsilon_{t-1},
\]

where \( |\alpha| \leq \tilde{\alpha} < 1 \) and \( |\beta| \leq \tilde{\beta} < \infty \). Here \( I_{t-1} = \{Y_t, Y_{t-1}, \ldots\} \) but \( I^*_{t-1} = \{Y_{t-1}, Y_{t-2}, \ldots, Y_1, \varepsilon_0\} \), and \( \varepsilon_0 \) is an initial value assumed for \( \varepsilon_0 \). By recursive substitution, we have

\[
\sum_{t=1}^{T} \{E[\sup_{\theta \in \Theta} |g(I_{t-1}, \theta) - g(I_{t-1}, \theta)|]^4\}^{\frac{1}{4}}
\]

\[
= \sum_{t=1}^{T} \left\{ E\left[ \sup_{\theta \in \Theta} \left( \beta \sum_{j=t-1}^{\infty} \alpha^j \varepsilon_{t-j-1} - \beta \alpha^{t-1} \varepsilon_0 \right) \right]^4 \right\}^{\frac{1}{4}}
\]

\[
\leq \tilde{\beta} \sum_{t=1}^{T} \left\{ E\left[ \sup_{\theta \in \Theta} \left( \sum_{j=0}^{\infty} \alpha^j (\varepsilon_{t-j} - \varepsilon_0) \right) \right]^4 \right\}^{\frac{1}{4}}
\]

\[
\leq \tilde{\beta} \sum_{t=1}^{T} |\tilde{\alpha}|^{t-1} \left[ (E[\varepsilon_0^4])^{\frac{1}{4}} \sum_{t=0}^{\infty} \tilde{\alpha}^t + (E[\varepsilon_0^4])^{\frac{1}{4}} \right] \leq C.
\]

Assumption A6 is a regularity condition on the kernel \( k(\cdot) \). It includes all commonly used kernels in practice. The condition of \( k(0) = 1 \) ensures that the asymptotic bias of the smoothed kernel estimator \( \hat{f}^{(0,1,0)}(\omega, 0, v) \) in (3.8) vanishes as \( T \to \infty \). The tail condition on \( k(\cdot) \) requires that \( k(z) \) decays to zero sufficiently fast as \( |z| \to \infty \). It implies \( \int_0^\infty (1 + z) k^2(z) dz < \infty \). For kernels with bounded support, such as the Bartlett and Parzen kernels, \( b = \infty \). For the Daniell and quadratic-spectral kernels, \( b = 1 \) and 2, respectively. These two kernels have unbounded support, and thus all \( T - 1 \) lags contained in the sample are used in constructing our test statistics. Assumption A7 is a condition on the weighting function \( W(\cdot) \) for the transform parameter \( v \). It is satisfied by the CDF of any symmetric continuous distribution with a finite fourth moment. Finally, Assumption A8 provides some covariance and fourth order cumulant conditions on \( \{\frac{\partial}{\partial \theta} g(I_{t-1}, \theta_0), \varepsilon_t\} \), which restrict the degree of the serial dependence in \( \{\frac{\partial}{\partial \theta} g(I_{t-1}, \theta_0), \varepsilon_t\} \). These conditions can be ensured by imposing more restrictive mixing and moment conditions.
on the process \( \frac{d}{dt} \) \( g(I_{t-1}, \theta_0), \varepsilon_t \). However, we do not do so to cover a sufficiently general class of DGPs. 

We now state the asymptotic distribution of the \( \hat{M}_a(p) \) tests under \( \mathbb{H}_0 \).

**Theorem 1.** Suppose Assumptions A1–A8 hold, and \( p = cT^\lambda \) for \( 0 < \lambda < (3 + \frac{1}{4b - 2})^{-1} \) and \( 0 < c < \infty \). (i) \( \hat{M}_1(p) \) \( \overset{d}{\rightarrow} \) \( N(0, 1) \) under \( \mathbb{H}_0 \). (ii) If in addition \( E(\varepsilon_t^2 | I_{t-1}) = \sigma^2 \) a.s., then \( \hat{M}_2(p) \) \( \overset{d}{\rightarrow} \) \( N(0, 1) \) under \( \mathbb{H}_0 \). (iii) If \( \{\varepsilon_t\} \) is i.i.d. \( (0, \sigma^2) \), then \( \hat{M}_3(p) \) \( \overset{d}{\rightarrow} \) \( N(0, 1) \).

As an important feature of \( \hat{M}_a(p) \), the use of the estimated model residuals \( \{\hat{\varepsilon}_t\} \) in place of the true unobservable errors \( \{\varepsilon_t\} \) has no impact on the limit distribution of \( \hat{M}_a(p) \). One can proceed as if the true parameter value \( \theta_0 \) was known and equal to \( \hat{\theta} \). The reason is that the convergence rate of the parametric parameter estimator \( \hat{\theta} \) to \( \theta_0 \) is faster than that of the nonparametric kernel estimator \( \hat{f}^{(0,1,0)}(\omega, 0, v) \) to \( f^{(0,1,0)}(\omega, 0, v) \). Consequently, the limit distribution of \( \hat{M}_a(p) \) is solely determined by \( \hat{f}^{(0,1,0)}(\omega, 0, v) \), and replacing \( \theta_0 \) by \( \hat{\theta} \) has no impact asymptotically. This delivers a convenient procedure, because no specific estimation method for \( \theta_0 \) is required. Of course, parameter estimation uncertainty in \( \hat{\theta} \) may have impact on the small sample distribution of \( \hat{M}_a(p) \). In small samples, one can use a bootstrap procedure similar to Hansen (1996) to obtain more accurate levels of the tests.

Because parameter estimation uncertainty in \( \hat{\theta} \) has no impact on the limit distribution of \( \hat{M}_1(p) \), \( \hat{M}_1(p) \) can be used to test the m.d.s. hypothesis for observed raw data with conditional heteroscedasticity of unknown form. No modification to the test statistic \( \hat{M}_1(p) \) or its limit distribution is needed. Lobato (2002) and Park and Whang (2003) proposed some nonparametric tests of the m.d.s. for observed raw data using the conditioning indicator function. They also allowed for conditional heteroscedasticity, and Park and Whang (2003) allowed for nonstationary conditioning variables. However, these tests only check a fixed lag order. Moreover, their limit distributions depend on the DGP and cannot be tabulated; resampling methods have to be used to obtain critical values on a case-by-case basis.

### 5. ASYMPTOTIC POWER

Our tests are derived without assuming an alternative model. To gain insight into the nature of the alternatives that our tests are able to detect, we now examine the asymptotic behaviour of \( \hat{M}_a(p) \) under \( \mathbb{H}_A \) in (2.3). For this purpose, we impose a condition on the serial dependence in \( \{\varepsilon_t\} \).

**Assumption A9.** \( \sum_{j=1}^{\infty} \sup_{u \in \mathbb{R}} |\sigma_j^{(1,0)}(0, v)| \leq C \).

**Theorem 2.** Suppose Assumptions A1 and A3–A9 hold, and \( p = cT^\lambda \) for \( 0 < \lambda < \frac{1}{2} \) and \( 0 < c < \infty \). Then as for \( a = 1, 2, 3, \)

\[
(p^{1/2} / T) \hat{M}_a(p) \xrightarrow{p} \left[ 2D \int_0^\infty k^4(z)dz \right]^{-1/2} \pi \int_{-\pi}^{\pi} f^{(0,1,0)}(\omega, 0, v) \\
- \int_0^{(0,1,0)}(\omega, 0, v)^2 d\omega dW(v) \\
= \left[ 2D \int_0^\infty k^4(z)dz \right]^{-1/2} \sum_{j=-\infty}^{\infty} \int |\sigma_j^{(1,0)}(0, v)|^2 dW(v)
\]

where \( D \equiv \sigma^4 \sum_{j=-\infty}^{\infty} \int |\sigma_j(u, v)|^2 dW(u)dW(v) = 2\pi \sigma^4 \int \int_{-\pi}^{\pi} |f(\omega, u, v)|^2 d\omega dW(u) dW(v) \).
The constant $D$ takes into account the impact of the serial dependence in conditioning variables $\{e^{it}\delta_l+j, j > 0\}$, which generally exists even under $\mathbb{H}_0$, due to the presence of the serial dependence in the conditional variance and higher order moments of $\{e_t\}$. This differs from the i.i.d. case, where $D = \sigma^2 \int \int |\sigma(0, v')|^2 dW(v) dW(v')$ depends only on the marginal distribution of $e_t$.

Suppose the autoregression function $E(e_t | e_{t-j}) \neq 0$ at some lag $j > 0$. Then we have $\int |\sigma_j^{(l,0)}(0, v)|^2 dW(v) > 0$ for any weighting function $W(\cdot)$ that is positive, monotonically increasing and continuous, with unbounded support on $\mathbb{R}$. As a consequence, $\lim_{T \to \infty} P[M_M(0) > C(T)] = 1$ for any constant $C(T) = o(T/p^{1/2})$. Therefore, $\hat{M}_M(p)$ has asymptotic unit power at any given significance level, whenever $E(e_t | e_{t-j})$ is nonzero at some lag $j > 0$.

We thus expect that $\hat{M}_M(p)$ has relatively omnibus power against a wide variety of linear and nonlinear alternatives with unknown lag structure, as is confirmed in our simulation below. It should be emphasized that the omnibus power property does not mean that $\hat{M}_M(p)$ is more powerful than any other existing tests against every alternative. In fact, just because $\hat{M}_M(p)$ has to take care of a wide range of possible alternatives, it may be less powerful against certain specific alternatives than the parametric test in finite samples. Nevertheless, the main advantage of $\hat{M}_M(p)$ is that it can eventually detect all possible model misspecifications that render $E(e_t | e_{t-j})$ nonzero at some lag $j > 0$. This avoids the blindness of searching for different alternatives when one has no prior information.

Because the existing tests for linearity in mean only consider a fixed order lag, they can easily miss misspecifications at higher lag orders. Of course, these tests could be used to check a large number of lags when a large sample is available. However, they are not expected to be powerful against many alternatives of practical importance, due to the loss of a large number of degrees of freedom. This power loss is greatly alleviated for our tests due to the role played by $k^2(\cdot)$. Most nonuniform kernels discount higher order lags. This enhances good power against the alternatives whose serial dependence decays to zero as lag order $j$ increases. Thus, our tests can check a large number of lags without losing too many degrees of freedom. This feature is not available for popular $\chi^2$-type tests with a large number of lags, which essentially give equal weighting to each lag. Equal weighting is not fully efficient when a large number of lags is considered.

Once the model $g(I_{t-1}, \theta)$ is rejected by our omnibus test $\hat{M}_M(p)$, one may like to go further to explore possible sources of model misspecification in mean. For this purpose, we can further differentiate the generalized spectral derivative $f^{(0,1,0)}(\omega, 0, v)$ with respect to $v$ and construct a sequence of tests similar in spirit to our $\hat{M}_M(p)$ tests. In particular, the derivatives $f_j^{(l,1,0)}(0, 0)$ with $l = 1, 2, 3, 4$ yield $\text{cov}(e_t, e_{t-j}), \text{cov}(e_t, e_{t-j}^2), \text{cov}(e_t, e_{t-j}^3)$ and $\text{cov}(e_t, e_{t-j}^4)$, respectively. Tests based on these derivatives can thus tell us whether there exists linear correlation, ARCH-in-mean, skewness-in-mean or kurtosis-in-mean effects, respectively. ARCH-in-mean effects are important in finance (Engle et al., 1987), and the recent literature also has documented time-varying skewness and kurtosis and their economic relevance in asset pricing (Harvey and Siddique, 1999, 2000).

The $\hat{M}_M(p)$ tests may not be very powerful in finite samples under some scenarios, because no direct use of lagged dependent variables and exogenous variables (if any) has been made. This is the case particularly when $\mu_t$ can be more effectively characterized by some vector $Z_t \in I_{t-1}$ than by the $e_{t-j}$, where $Z_t$ may contain lagged dependent variables and/or exogenous variables. To improve power, we may extend our approach to include $Z_t$ as the conditioning variables.

11. Since $\int \int |f_j^{(0,1,0)}(\omega, 0, v) - f_j^{(0,1,0)}(0, 0, v)|^2 dW(v) dW(v')$ is strictly positive whenever $E(e_t | e_{t-j}) \neq 0$ for some lag $j > 0$, upper-tailed asymptotic $N(0, 1)$ critical values (e.g. 1.645 at the 5% level) should be used.
Put \( X_t \equiv (Z_t', \varepsilon_t)' \), and define

\[
\sigma_{\varepsilon X, j}^{(1,0)}(0, \nu) = \text{cov}(i \varepsilon_t, e^{i \nu' X_{t-j}}), \quad \nu \in \mathbb{R}^{d+1},
\]

where \( d \) is the dimension of \( Z_t \). \(^{12}\) The associated test statistic of \( \mathbb{H}_0 \) that is robust to conditional heteroscedasticity and higher order moments of unknown form is given as follows:

\[
\hat{M}_{\varepsilon X}(p) = \left[ \sum_{j=1}^{T-1} k^2(j/p)(T-j) \int_{\mathbb{R}^{d+1}} |\hat{\sigma}_{\varepsilon X}^{(1,0)}(0, \nu)|^2 dW(\nu) - \hat{C}_{\varepsilon X, 1}(p) \right]/\sqrt{\tilde{D}_{\varepsilon X, 1}(p)},
\]  

(5.1)

where \( \hat{\sigma}_{\varepsilon X}^{(1,0)}(0, \nu) = \frac{\partial}{\partial u} \hat{\sigma}_{\varepsilon X}(u, \nu)|_{u=0}, \hat{\sigma}_{\varepsilon X}(u, \nu) = \hat{\phi}_{\varepsilon X, j}(u, \nu) - \hat{\phi}_{\varepsilon X, j}(0, \nu), \)

\( \hat{\phi}_{\varepsilon X, j}(u, \nu) = (T - j)^{-1} \sum_{t=j+1}^{T} e^{iu'X_{t-j}} \), and \( \hat{X}_t \equiv (Z_t', \hat{\varepsilon}_t)' \). In addition, \( \hat{C}_{\varepsilon X, 1}(p) \) and \( \tilde{D}_{\varepsilon X, 1}(p) \) are defined in the same way as \( \hat{C}_1(p) \) and \( \tilde{D}_1(p) \) in (3.11) with \( \hat{\gamma}_t(\nu) \) replaced by \( \hat{\gamma}_t(X_{t-j}) \equiv e^{i \nu' \hat{X}_{t-j}} - \hat{\phi}_X(\nu) \), where \( \hat{\phi}_X(\nu) = T^{-1} \sum_{j=1}^{T} e^{i \nu' X_t} \). For simplicity, we can use a product weighting function \( W(\nu) = \Pi_{j=1}^{d+1} W(v_j) \), where \( W(\cdot) \) satisfies Assumption A7. The test statistic \( \hat{M}_{\varepsilon X}(p) \) involves \( (d+1) \)- and \( 2(d+1) \)-dimensional numerical integrations, which can be evaluated by simulation when \( d \) is large.

Under suitable conditions, we can show that \( \hat{M}_{\varepsilon X}(p) \xrightarrow{p} N(0, 1) \) under \( \mathbb{H}_0 \), and

\[
(p^{1/2}/T)\hat{M}_{\varepsilon X}(p) \xrightarrow{p} 2D_X \int_{0}^{\infty} k^4(z)dz \left[ \sum_{j=1}^{\infty} \int |\sigma_{\varepsilon X, j}^{(1,0)}(0, \nu)|^2 dW(\nu) \right],
\]

under \( \mathbb{H}_A \), where \( D_X \equiv \sigma^4 \sum_{j=1}^{\infty} \int \int |\sigma_{\varepsilon X, j}(u, \nu)|^2 dW(u) dW(\nu) \) and \( \sigma_{\varepsilon X, j}(u, \nu) = \text{cov}(e^{iu'X_t}, e^{i \nu' X_{t-j}}) \). Thus, this test can detect all model misspecifications in mean that render \( E(\varepsilon_t | X_{t-j}) \equiv E(\varepsilon_t | Z_{t-j}, \varepsilon_{t-j}) \neq 0 \) for some \( j > 0 \).

A plausible alternative approach to testing \( \mathbb{H}_0 \) in (2.2) is to consider a test based on the statistic

\[
\sum_{j=1}^{T-1} k^2(j/p)(T-j) \left[ \frac{1}{T-j} \sum_{t=j+1}^{T} m^2_j(\hat{\varepsilon}_{t-j}) \right],
\]

(5.2)

where \( m_j(\cdot) \) is a smoothed nonparametric estimator for the autoregression function \( E(\varepsilon_t | \varepsilon_{t-j}) \) at lag \( j \). This test also avoids the curse of dimensionality and can detect the same class of global alternatives to \( \mathbb{H}_0 \) as the \( \hat{M}_d(p) \) tests. Moreover, the estimator \( m_j(\cdot) \) is often of more direct interest in practice. Nevertheless, unlike \( \hat{\gamma}_t(0, \nu), \hat{m}_j(\cdot) \) involves a smoothing parameter, say a bandwidth \( h_j \) (for simplicity, one can set \( h_j = h \equiv h(T) \) for all \( j > 0 \)). Closely associated with the choice of the bandwidth \( h \), the test based on (5.2) is expected to have poor levels even for rather large sample sizes, as was documented in Hjellvik and Tjøstheim (1996), who used a statistic similar to (5.2) to test linearity for observed raw data, with a fixed \( p \) and the truncated (uniform) kernel \( k(z) = 1(|z| \leq 1) \). Hjellvik and Tjøstheim (1996) pointed out that in a Taylor series expansion of (5.2), asymptotically negligible higher order terms depend on \( h \) and are nearly of the same order of magnitude as the dominating term that determines the asymptotic distribution. As a consequence, to retain the dominating term and to neglect the others will give poor approximations in finite samples. \(^{13}\)

12. The Fourier transform, \( f_{\varepsilon X}^{(0,1,0)}(\omega, 0, \nu) = (2\pi)^{-1} \sum_{j=-\infty}^{\infty} \sigma_{\varepsilon X, j}^{(1,0)}(0, \nu)e^{-ij\omega}, \omega \in [-\pi, \pi] \), may be viewed as a generalized cross-spectrum between \( \varepsilon_t \) and \( X_t \).

13. Of course, one can use bootstrap to obtain correct levels for this test. But this will complicate the implementation of the test. In particular, the naive bootstrap is not suitable, because there exists serial dependence in the variance and higher order moments.
6. DATA-DRIVEN LAG ORDER

A practical issue in implementing our tests is the choice of the lag order $p$. As an advantage, our smoothing generalized spectral approach can provide a data-driven method to choose $p$, which, to some extent, lets data themselves speak for a proper $p$. Before discussing any specific method, we first justify the use of a data-driven lag order, $\hat{p}$ say. Here, we impose a Lipschitz continuity condition on $k(\cdot)$. This condition rules out the truncated kernel $k(z) = 1(|z| \leq 1)$, but it still includes most commonly used nonuniform kernels.

**Assumption A10.** For any $x, y \in \mathbb{R}$, $|k(x) - k(y)| \leq C|x - y|$ for some constant $C < \infty$.

**Theorem 3.** Suppose Assumptions A1–A8 and A10 hold, and $\hat{p}$ is a data-driven bandwidth such that $\hat{p}/p = 1 + O_P(p^{-\frac{1}{2}(\beta-1)})$ for some $\beta > (2b - \frac{1}{2})/(2b - 1)$, where $b$ is as in Assumption A6, and $p$ is a nonstochastic bandwidth with $p = cT^\lambda$ for $0 < \lambda < (3 + \frac{1}{2(\beta-2)})^{-1}$ and $0 < c < \infty$. Then (i) $\hat{M}_1(\hat{p}) - \hat{M}_1(p) \xrightarrow{p} 0$ and $\hat{M}_1(\hat{p}) \xrightarrow{d} N(0, 1)$ under $\mathbb{H}_0$. (ii) If in addition $E(e_i^2 | I_{t-1}) = \sigma^2$ a.s., then $\hat{M}_2(\hat{p}) - \hat{M}_2(p) \xrightarrow{p} 0$ and $\hat{M}_2(\hat{p}) \xrightarrow{d} N(0, 1)$ under $\mathbb{H}_0$. (iii) If $\{e_i\}$ is i.i.d. $(0, \sigma^2)$, then $\hat{M}_3(\hat{p}) - \hat{M}_3(p) \xrightarrow{p} 0$ and $\hat{M}_3(\hat{p}) \xrightarrow{d} N(0, 1)$.

Thus, as long as $\hat{p}$ converges to $p$ sufficiently fast, the use of $\hat{p}$ instead of $p$ has no impact on the limit distribution of $\hat{M}_a(\hat{p})$. This is an additional “nuisance parameter-free” property.

Theorem 3 allows for a wide range of admissible rates for $\hat{p}$. One plausible choice of $\hat{p}$ is the nonparametric plug-in method similar to Hong (1999, Theorem 2.2). It minimizes an asymptotic integrated mean squared error (IMSE) criterion for the estimator $f^{(0,1,0)}(\omega, 0, v)$ in (3.8). Consider some “pilot” generalized spectral derivative estimators based on a preliminary bandwidth $\tilde{p}$:

$$
\hat{f}^{(0,1,0)}(\omega, 0, v) = \frac{1}{2\pi} \sum_{j=1-T}^{T-1} \frac{1}{(1 - |j|/T)} \frac{1}{k(j/\tilde{p})} \hat{\sigma}_j^{(1,0)}(0, v)e^{-ij\omega},
$$

$$
\hat{f}^{(q,1,0)}(\omega, 0, v) = \frac{1}{2\pi} \sum_{j=1-T}^{T-1} \frac{1}{(1 - |j|/T)} \frac{1}{k(j/\tilde{p})} \hat{\sigma}_j^{(1,0)}(0, v)|j|^qe^{-ij\omega},
$$

where the kernel $\tilde{k}(\cdot)$ need not be the same as the kernel $k(\cdot)$ used in (3.8). For example, $\tilde{k}(\cdot)$ can be the Bartlett kernel while $k(\cdot)$ is the Parzen kernel. Note that $\hat{f}^{(0,1,0)}(\omega, 0, v)$ is an estimator for $f^{(0,1,0)}(\omega, 0, v)$ and $\hat{f}^{(q,1,0)}(\omega, 0, v)$ is an estimator for the generalized spectral derivative

$$
f^{(q,1,0)}(\omega, 0, v) = \frac{1}{2\pi} \sum_{j=-\infty}^{\infty} \sigma_j^{(1,0)}(0, v)|j|^qe^{-ij\omega}.
$$

For the kernel $k(\cdot)$, suppose there exists some $q \in (0, \infty)$ such that $0 < k(q) \equiv \lim_{z \to 0} \frac{1 - k(z)}{|z|^q} < \infty$. Then we define the plug-in bandwidth

$$
\hat{p}_0 = \hat{c}_0 T^{\frac{1}{2q+1}},
$$

where the tuning parameter estimator

$$
\hat{c}_0 = \left[ \frac{2q(k(q))^2}{\int_{-\infty}^{\infty} k^2(z)dz} \left( \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} |f^{(q,1,0)}(\omega, 0, v)|^2 d\omega dW(v) \right)^{\frac{1}{2q+1}} \right]^{\frac{1}{2q+1}} = \left[ \frac{2q(k(q))^2}{\int_{-\infty}^{\infty} k^2(z)dz} \sum_{j=1-T}^{T-1} (T - |j|) |k^2(j/\tilde{p})|^q \int |\hat{\sigma}_j^{(1,0)}(0, v)|^2 dW(v) \right]^{\frac{1}{2q+1}},
$$

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and \( \hat{R}(j) = (T - |j|)^{-1} \sum_{t=|j|+1}^T \hat{\varepsilon}_t \hat{\varepsilon}_{t-|j|} \). Note that \( \hat{p}_0 \) is real-valued. One can take its integer part, and the impact of integer-clipping is expected to be negligible.

The data-driven \( \hat{p}_0 \) in (6.4) involves the choice of a preliminary bandwidth \( \hat{p} \), which can be fixed or grow with the sample size \( T \). If \( \hat{p} \) is fixed, \( \hat{p}_0 \) still generally grows at rate \( T^\vartheta \hat{p}^{1 + \vartheta} \) under \( \mathbb{H}_A \), but \( \hat{c}_0 \) does not converge to the optimal tuning constant \( c_0 \) (say) that minimizes the IMSE of \( f^{(0,1,0)}(\omega, 0, v) \). This is a parametric plug-in method. Alternatively, following Hong (1999), we can show that when \( \hat{p} \) grows with \( T \) properly, the data-driven bandwidth \( \hat{p}_0 \) in (6.4) will minimize an asymptotic IMSE of \( f^{(0,1,0)}(\omega, 0, v) \). The choice of \( \hat{p} \) is somewhat arbitrary, but we expect that it is of secondary importance. This is confirmed in our simulation and empirical application below.15

We emphasize that the data-driven \( \hat{p} \) based on the IMSE criterion generally will not maximize the power of \( \hat{M}_a(p) \). A more sensible alternative would be to develop a data-driven \( \hat{p} \) using a power criterion, or a criterion that trades off level distortion and power loss. This will necessitate higher order asymptotic analysis and is beyond the scope of this paper. We are content with the IMSE criterion here. Our simulation experience suggests that the power of our tests seems to be relatively flat in the neighbourhood of the optimal lag order that maximizes the power, and \( \hat{p}_0 \) in (6.4) performs reasonably well in finite samples. Nevertheless, the issue of the optimal data-driven \( \hat{p} \) for our tests is far from being resolved from a theoretical perspective.

7. MONTE CARLO EVIDENCE

We now investigate the finite sample performance of our \( \hat{M}_a(p) \) tests. While our tests can be used to test nonlinear conditional mean models, we focus on testing linearity in mean, which has attracted a lot of attention in the literature. Because our tests are derived without specifying an alternative, we will compare them with a number of popular linearity tests of similar spirit, namely those of Tsay (1986), White (1989) and Hamilton (2001). The limit distributions of these tests are derived under conditional homoscedasticity or i.i.d. \( N(0, \sigma^2) \). Their robust versions under conditional heteroscedasticity of unknown form have not been available.

7.1. Simulation design

7.1.1. Level. To examine the levels of the tests under \( \mathbb{H}_0 \), we consider the following DGPs:

\[
\text{DGP S.1 [AR(1)-i.i.d. (0, 1)]:} \quad Y_t = 0.5Y_{t-1} + \varepsilon_t, \quad \varepsilon_t \sim \text{i.i.d. } N(0, 1),
\]

\[
\text{DGP S.2 [AR(1)-ARCH(1)]:} \quad \varepsilon_t = h_t^{1/2}z_t, \quad h_t = 0.43 + 0.5\varepsilon_{t-1}^2, \quad z_t \sim \text{i.i.d. } N(0, 1).
\]

14. For the \( \hat{M}_X(p) \) test in (5.1), we need to modify \( \hat{c}_0 \) as follows: \( \hat{\sigma}_j(1,0) \) in the numerator of \( \hat{c}_0 \) should be replaced by \( \hat{\sigma}_j(1,0) \) as used in (5.1), and \( \hat{\rho}_j(\cdot, -v) \) in the denominator should be replaced by \( \hat{\rho}_j(X_t, -v) = \hat{\varphi}_{X_t,j}(v, u) \hat{\varphi}_{X_t,j}(0, v) \hat{\varphi}_{X_t,j}(0, -v) \), where \( \hat{\varphi}_{X_t,j}(u, v) = (T - |j|)^{-1} \sum_{t=|j|+1}^T \varepsilon_{t,j}^{\mu've'X_t+i'v'X_{t-|j|}} \), and \( \hat{\varepsilon}_t \) is \( (Z_t, \varepsilon_t) \). Moreover, the univariate weighting function \( W(v) \) should be replaced by the product weighting function \( W(v) = \prod_{j=1}^{d+1} W(v_j) \), where \( v = (v_1, \ldots, v_{d+1}) \).

15. The tuning parameter estimator \( \hat{c}_0 \) will converge to zero under \( \mathbb{H}_0 \). To ensure \( \hat{p}_0 \to \infty \), we can use the formula (6.4) supplemented with a slow-growing lower bound (say \( \rho_0 \)) such that \( \rho_0 = \max(\ln T, \hat{p}_0) \). The choice of the slow-growing lower bound \( \ln T \) is arbitrary, but it will not affect the IMSE-optimal rate \( \hat{p}_0 \) under \( \mathbb{H}_A \), when \( T \) is sufficiently large.
Under these DGPs, the linear AR(1) model
\[ g(I_{t-1}, \theta) = \theta_1 + \theta_2 Y_{t-1} \]  
(7.1)
is correctly specified for \( E(Y_t \mid I_{t-1}) = 0.5Y_{t-1} \). The parameter \( \theta_0 \equiv (0, 0.5)' \) can be estimated consistently by the OLS estimator \( \hat{\theta} \). The model error \( \{\varepsilon_t(\theta_0)\} \) is conditionally homoscedastic under DGP S.1; all tests considered are asymptotically valid under this DGP. Under DGP S.2, \( \{\varepsilon_t(\theta_0)\} \) is conditionally heteroscedastic; only \( \hat{M}_1(\hat{\theta}_0) \) has a valid limit distribution. This allows us to examine the importance of taking into account conditional heteroscedasticity. We have chosen parameter values in DGP S.2 such that \( E[\varepsilon^4_t(\theta_0)] < \infty \). To examine the level, we consider three sample sizes: \( T = 100, 250 \) and 500.

7.1.2. Power. Next, we examine the power of the tests for neglected nonlinearity or dynamic misspecification in mean (i.e. lag order misspecification). Because the tests for linearity in mean are not valid under conditional heteroscedasticity, we will focus on homoscedastic errors in power comparison. We consider the following DGPs:

- **DGP P.1 [Bilinear(1)]:** \( Y_t = 0.5Y_{t-1} + 0.6Y_{t-1}\varepsilon_{t-1} + \varepsilon_t \),
- **DGP P.2 [NMA(1)]:** \( Y_t = 0.5Y_{t-1} - 0.6\varepsilon_{t-1}^2 + \varepsilon_t \),
- **DGP P.3 [EXP-AR(1)]:** \( Y_t = 0.5Y_{t-1} + 10Y_{t-1}\exp(-Y^2_{t-1}) + \varepsilon_t \),
- **DGP P.4 [SETAR(1)]:** \( Y_t = \begin{cases} 0.5Y_{t-1} + \varepsilon_t & \text{if } Y_{t-1} \leq 0, \\ -0.5Y_{t-1} + \varepsilon_t & \text{if } Y_{t-1} > 0, \end{cases} \)
- **DGP P.5 [STAR(1)]:** \( Y_t = 1 - 0.5Y_{t-1} - (4 + 0.4Y_{t-1})G(\alpha Y_{t-1}) + \varepsilon_t \),
  where \( G(z) = [1 + \exp(-z)]^{-1} \),
- **DGP P.6 [ARMA(1, 1)]:** \( Y_t = 0.5Y_{t-1} + 0.5\varepsilon_{t-1} + \varepsilon_t \),
- **DGP P.7 [NMA(5)]:** \( Y_t = 0.5Y_{t-1} + \sum_{j=1}^{5} 0.5^j \varepsilon_{t-j}^2 + \varepsilon_t \),
- **DGP P.8 [SIGN AR(6)]:** \( Y_t = 1(Y_{t-6} > 0) - 1(Y_{t-6} < 0) + \varepsilon_t \),

where \( \{\varepsilon_t\} \) is i.i.d. \( N(0, 1) \).

DGPs P.1–P.5 are taken from Tsay (2001). They cover bilinear autoregressive, nonlinear MA, exponential autoregressive, self-exciting threshold, and smooth transition threshold processes. These DGPs allow us to examine the power of the tests against various neglected nonlinearities in mean. DGP P.6 is a linear ARMA(1, 1) process, under which the AR(1) model in (7.1) suffers from dynamic misspecification rather than neglected nonlinearity in mean. Note that DGPs P.1–P.6 are all first order dynamic processes. Our tests, which employ several lags, may not be expected to be the most powerful against them. To highlight our approach, we include DGPs P.7 and P.8. DGP P.7 is an extended nonlinear MA process up to lag 5, with declining coefficients. Declining weights reflect the stylized fact that economic behaviours are usually more influenced by the recent past events than the remote past events. DGP P.8 is a sign autoregressive process with a time delay of six periods. Time delay is an important feature in nonlinear time series (Tong (1990), Granger and Teräsvirta (1993, p. 8)). After removing the best least square approximation to each of DGPs P.1–P.8, we find that for all these DGPs, the generalized spectral derivative \( m(\omega) \) in (3.5) of the model error \( \varepsilon_t \equiv \varepsilon_t(\theta_0) \), where \( \theta_0 = \lim \hat{\theta} \), is not flat over the frequency \( \omega \).  

16. We also consider a GARCH process with an infinite fourth order moment. The level performance of the generalized spectral derivative tests is similar.

17. In checking whether \( m(\omega) \) is flat, we use a numerical method. We first generate a data of 10,000 observations and obtain the OLS residuals of the AR(1) model in (7.1) fitted to the simulated data. Then we obtain the kernel estimator.
Thus, our tests are expected to be able to detect model misspecifications under all these DGPs for the sample size \( T \) sufficiently large, in light of Theorem 2. We will examine how powerful our tests are relative to the other tests for two sample sizes: \( T = 100 \) and 250, respectively.

### 7.2. Computation of test statistics

To compute the test statistics of Tsay (1986), White (1989) and Hamilton (2001), one has to determine how many lags \((p)\) should be used in the test vector \( Z_t \equiv (Y_{t-1}, \ldots, Y_{t-p})' \). We choose \( p = 1, 2 \) and 5 for these tests.\(^{18}\) Tsay’s (1986) test statistic is computed as follows: (i) regress \( Y_t \) on 1 and \( Y_{t-1} \) and save the estimated residuals \( \{\hat{\varepsilon}_t\} \); (ii) let \( H_t \) be the vector containing \( \frac{1}{2} p(p + 1) \) cross-product terms of the components of \( Z_t \), in the form \( Y_{t-j} Y_{t-k} \), where \( j \geq k \) and \( j, k = 1, \ldots, p \). Then regress \( H_t \) on 1 and \( Y_{t-1} \) and save the vector-valued residuals \( \{\hat{\varepsilon}_t\} \); (iii) regress \( \hat{\varepsilon}_t \) on \( \hat{\varepsilon}_t \) and save the estimated residuals \( \{\hat{\xi}_t\} \); (iv) compute Tsay’s statistic

\[
\text{TSAY}(p) = \frac{\left(\sum_{t=1}^{T} \hat{\varepsilon}_t \hat{\varepsilon}_t' \right) \left(\sum_{t=1}^{T} \hat{\xi}_t \hat{\xi}_t' \right)^{-1} \left(\sum_{t=1}^{T} \hat{\varepsilon}_t \hat{\xi}_t\right)}{\left(\sum_{t=1}^{T} \hat{\xi}_t^2\right)} \left( T - p - \frac{1}{2} p(p + 1) \right) - 1,
\]

and compare it to the \( F\left[\frac{1}{2} p(p + 1), T - \frac{1}{2} p(p + 3) - 1\right] \) distribution.\(^{19}\)

White’s (1989) neural network test statistic is computed as follows: (i) regress \( Y_t \) on 1 and \( Y_{t-1} \) and save the estimated residuals \( \{\hat{\varepsilon}_t\} \); (ii) construct the test function \( \psi_{jt} = \psi(Y_{jt}) \), \( j = 1, \ldots, q \), where \( \psi(\cdot) \) is the activation function, \( \Gamma_j \equiv (\gamma_0, \gamma_j')' \) is randomly drawn from a uniform distribution on \([-2, 2]^p+1\), and \( q \) is a pre-specified number of hidden units. Following Lee et al. (1993), we scale \( \{Y_t\} \) to \([0, 1]\), using the logistic function \( \psi(u) = \left[1 + \exp(-u)\right]^{-1} \), and set \( q = 10 \); (iii) compute the principal components of \( \psi_t \equiv (\psi_{1t}, \ldots, \psi_{qt})' \) and retain the \( q^* \) largest principal components \( \psi^* \) except for the largest one. We set \( q^* = 3 \); (iv) regress \( \hat{\varepsilon}_t \) on 1, \( Y_{t-1} \), and \( \psi^*_t \), and obtain \( R^2 \), the squared unccentred multi-correlation coefficient; (v) compute the test statistic \( \text{NN}(p) = TR^2 \), and compare it with \( \chi^2_{q^*} \).

In addition to the lag order \( p \), Hamilton’s (2001) test involves choosing a covariance function \( H_p(\cdot) \) for the underlying random field, and the value of the associated \( p \times 1 \) parameter vector \( g \). Hamilton’s (2001) test statistic is computed as follows: (i) set \( g_j = 2/(p \hat{\sigma}_j^2) \); \( j = 1, \ldots, p \), where \( \hat{\sigma} \) is the sample standard deviation of \( Y_{t-j} \); (ii) calculate the \( T \times T \) matrix \( H \) whose \((t, s)\)-th element is given by \( H_{ps} = \sum_{j=1}^{p} g_j^2 (Y_{t-j} - Y_{t-j})^2 \); (iii) for the pre-specified covariance function \( H_p(\cdot) \) given in Hamilton (2001, Theorem 2.2 or Table I); (iii) regress \( Y_t \) on 1 and \( Y_{t-1} \), with the estimated residuals \( \{\hat{\varepsilon}_t\} \), the residual sample variance \( \hat{\sigma}^2 \equiv \hat{\varepsilon}' \hat{\varepsilon} / (T - 2) \) and the \( T \times T \) projection matrix \( M = IT - X(X'X)^{-1}X \) for the \( T \times 2 \) matrix whose \( t \)-th row is \( (1, Y_{t-1}) \); (iv) compute the test statistic

\[
\text{HM}(p) = \frac{[\hat{\varepsilon}' H \hat{\varepsilon} - \hat{\sigma}^2 \text{tr}(MM^H)]^2}{\hat{\sigma}^4 [2 \text{tr}[(MM^H - (T - 2) - 1)M \text{tr}(MM^H)^2]]}.
\]

and compare it to the \( \chi^2_1 \) distribution.

\(^{18}\) It is not realistic to choose \( p \) as large as \( p = 20 \) (say) for these existing tests when \( T = 100 \). For example, Tsay’s (1986) test would have \( \frac{1}{2} p(p + 1) = 210 \) variables in an auxiliary regression, which is larger than the sample size \( T \). In contrast, the choice of \( p = 20 \) when \( T = 100 \) is reasonable for our generalized spectral derivative tests.

\(^{19}\) In fact, the effective sample size in some auxiliary regressions is \( T - p \), so we have replaced \( T \) with \( T - p \) in computing the test statistics of Tsay (1986), White (1989) and Hamilton (2001).
To compute $\hat{M}_a(\hat{p}_0)$, we use the $N(1,0)$ CDF truncated on $[-3,3]$ for the weighting function $W(\cdot)$. We use the Bartlett kernel $k_B(z) = (1 - |z|)I(|z| \leq 1)$ for $k(\cdot)$, which has a bounded support and is computationally efficient. Our simulation experience suggests that the choices of $W(\cdot)$ and $k(\cdot)$ have little impact on both the level and the power of our tests. We choose a data-driven $\hat{p}_0$ via the plug-in method in (6.4), with the Bartlett kernel for $k(\cdot)$ used in the preliminary generalized spectral density estimators in (6.1) and (6.2). To examine the impact of the choice of preliminary bandwidth $\hat{p}$, we consider $\hat{p} = c((k_B^{(1)})^2 / \int k_B^2(u)du)^{1/2} = c(10T)^{1/2}, c > 0$. This rate is optimal for estimating the preliminary generalized spectral density derivative $\tilde{f}^{(1,1,0)}(\omega, 0, v)$. We choose $c = 2, 4, 6$, which cover a wide range of values for $\hat{p} : [7.96, 23.87]$ for $T = 100, [9.56, 28.69]$ for $T = 250$, and $[10.98, 32.96]$ for $T = 500$.

7.3. Monte Carlo evidence

Table 1 reports the empirical rejection rates of the tests under $\mathbb{H}_0$ at the 10% and 5% levels, using the asymptotic theory. Under DGP S.1 (homoscedastic errors), all $\hat{M}_a(\hat{p}_0)$ tests underreject $\mathbb{H}_0$ but not excessively; the tests $\hat{M}_2(\hat{p}_0)$ and $\hat{M}_3(\hat{p}_0)$ derived under conditional homoscedasticity and i.i.d., respectively, have better levels than $M_1(\hat{p}_0)$. There is some tendency that a larger preliminary lag order $\hat{p}$ gives a better level for all $\hat{M}_a(p)$ tests. Under DGP S.2 (ARCH errors), $\hat{M}_2(\hat{p}_0)$ and $\hat{M}_3(\hat{p}_0)$ display strong overrejection, as is expected. In contrast, $\hat{M}_1(\hat{p}_0)$ shows

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20. We have also used the Parzen kernel (not reported). Although the data-driven lag order $\hat{p}_0$ is substantially smaller, the test statistics are rather similar to those based on the Bartlett kernel in most cases.
substantial underrejection for $T = 100$, but improves as $T$ increases. Unlike under DGP S.1, a larger $p$ does not give a better level for $\hat{M}_1(\hat{p}_0)$.

Next, we turn to the levels of TSAY($p$), NN($p$) and HM($p$), which are valid tests under conditional homoscedasticity. Under DGP S.1, these tests have better levels than the $\hat{M}_a(\hat{p}_0)$ tests, though not in every case. Under DGP S.2, TSAY($p$) and NN($p$) show very strong overrejections. The HM($p$) test also shows some overrejections when $p = 1, 2$, but interestingly, HM(5) displays underrejection.

Table 2 reports the level-corrected power at the 10% and 5% levels under DGPs P.1–P.8. The empirical critical values are obtained under DGP S.1. We compare $\hat{M}_2(\hat{p}_0)$ and $\hat{M}_3(\hat{p}_0)$ with TSAY($p$), NN($p$) and HM($p$), all of which are derived under conditional homoscedasticity. Under DGP P.1 (bilinear(1)) and DGP P.2 (nonlinear MA(1)), $\hat{M}_2(\hat{p}_0)$ and $\hat{M}_3(\hat{p}_0)$ are among the most powerful tests. The power of TSAY($p$), NN($p$) and HM($p$) is sensitive to the choice of $p$. In contrast, the power of $\hat{M}_2(\hat{p}_0)$ and $\hat{M}_3(\hat{p}_0)$ is relatively robust to the choice of preliminary lag order $\hat{p}$. Note that the heteroscedasticity-robust test $\hat{M}_1(\hat{p}_0)$ is less powerful than $\hat{M}_2(\hat{p}_0)$ and $\hat{M}_3(\hat{p}_0)$ under DGPs P.1 and P.2.

Under DGP P.3 (EXP-AR(1)), NN($p$) and HM($p$) are the most powerful for $p = 1, 2$ and $T = 100$, while TSAY($p$) is the least powerful. The $\hat{M}_a(\hat{p}_0)$ tests are powerful, though not as powerful as HM($p$) and NN($p$) with $p = 1, 2$. All $\hat{M}_a(\hat{p}_0)$ tests are equally powerful. Under DGP P.4 (SETAR(1)), TSAY(1) and NN(1) are the most powerful, followed by HM(1). The $\hat{M}_a(\hat{p}_0)$ tests are equally powerful. They are not as powerful as TSAY(1), NN(1) and HM(1), but they substantially outperform TSAY(5), NN(5) and HM(5). Again, this highlights the robust power property of $\hat{M}_a(\hat{p}_0)$ relative to the existing tests.

Under DGP P.5 (STAR(1)), HM($p$) is the most powerful, followed by NN($p$) and then by TSAY($p$). The $\hat{M}_a(\hat{p}_0)$ tests are the least powerful against this DGP when $T = 100$, but their power quickly catches up when $T = 250$. The relative ranking of the tests is quite different under DGP P.6 (ARMA(1, 1)). Although it is a first order ARMA process, all $\hat{M}_a(\hat{p}_0)$ tests are very powerful and their powers are comparable to the most powerful test NN(2). Moreover, the powers of $\hat{M}_a(\hat{p}_0)$ are robust to the choice of the preliminary lag order $\hat{p}$. In contrast, TSAY(1), NN(1) and HM(1) have no power at all even if $T$ increases. All TSAY($p$) tests have little or low power.

The relatively omnibus and robust power performance of the $\hat{M}_a(\hat{p}_0)$ tests under DGP P.1–P.6 is encouraging given the fact that DGP P.1–P.6 are all first order dynamic processes whereas $\hat{M}_a(\hat{p}_0)$ employs many lags. Such omnibus and robust power apparently comes from the use of the characteristic function and the downward weighting kernel $k(\cdot)$ for lags, which highlights the advantages of the generalized spectrum. In fact, additional merits of $\hat{M}_a(\hat{p}_0)$ are further highlighted under DGPs P.7 and P.8. Under DGP P.7 (NMA(5)), which has a declining weight as lag order increases, the $\hat{M}_a(\hat{p}_0)$ tests are the most powerful and their powers are robust to the choice of the preliminary lag order $\hat{p}$. TSAY($p$) also has good power and dominates NN($p$) and HM($p$). Interestingly, although NMA(5) is a fifth order dynamic process, the maximal power of TSAY($p$), NN($p$) and HM($p$) occurs when $p = 2$ instead of $p = 5$.

Under DGP P.8 (SIGN AR(6)), where nonlinearity occurs at lag 6, TSAY($p$), NN($p$) and HM($p$) all have no low power because $p < 6$. This is the case even when $T$ increases. Thus, it is important to select a suitable lag order for these tests, but this requires knowledge of the alternative. In contrast, the $\hat{M}_a(\hat{p}_0)$ tests are very powerful, and they require no knowledge of the lag structure in the DGP.

In summary, we observe:

1. The empirical levels of the $\hat{M}_a(\hat{p}_0)$ tests are smaller than the nominal levels, but they improve as the sample size increases. Under homoscedastic errors, the homoscedasticity-
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Notes: (1) DGP P.1, \( Y_t = 0.5Y_{t-1} + 0.6Y_{t-1}e_{t-1} + e_t \); DGP P.2, \( Y_t = 0.5Y_{t-1} - 0.6e_{t-1}^2 + e_t \); DGP P.3, \( Y_t = 0.5Y_{t-1} + 10Y_{t-1} \exp(-Y_{t-1}^2) + e_t \); DGP P.4, \( Y_t = 0.5Y_{t-1}I(Y_{t-1} \leq 0) - 0.5Y_{t-1}I(Y_{t-1} > 0) + e_t \); DGP P.5, \( Y_t = 1 - 0.5Y_{t-1} + (-4 - 0.4Y_{t-1})G(\alpha Y_{t-1}) + e_t \), where \( G(\zeta) = (1 + \exp(\zeta))^{-1} \); DGP P.6, \( Y_t = 0.5Y_{t-1} + 0.5e_{t-1}^2 + e_t \); DGP P.7, \( Y_t = 0.5Y_{t-1} + \sum_{j=1}^{5} 0.5^j e_{t-j} \); DGP P.8, \( Y_t = 1(Y_{t-6} > 0) - 1(Y_{t-6} < 0) + e_t \), where \( e_t \sim \text{i.i.d.} \ N(0, 1) \); (2) 500 iterations.
specific tests, \( \hat{M}_2(\hat{p}_0) \) and \( \hat{M}_3(\hat{p}_0) \), have better levels than the heteroscedasticity-robust test \( \hat{M}_1(\hat{p}_0) \). Under ARCH errors, \( \hat{M}_1(\hat{p}_0) \) continues to have reasonable levels (though still underrejection), but all homoscedasticity-specific tests strongly overreject the correct model.

2. The powers of TSAY\((p)\), NN\((p)\) and HM\((p)\) are rather sensitive to the choice of the lag order \( p \), and the maximal powers of these tests usually do not arise when \( p \) matches the true lag order of the DGP. It is often beneficial to use more lags than those specified in the null model, but there is no rule to select an optimal lag order for these tests. In contrast, the \( \hat{M}_d(\hat{p}_0) \) tests have relatively robust power with respect to the choice of the preliminary lag order \( \hat{p} \), and they require no knowledge of the lag structure of the potential alternative.

3. The \( \hat{M}_d(\hat{p}_0) \) tests are not always the most powerful in detecting each of the eight DGPs. However, they have relatively omnibus power against all eight DGPs provided the sample size is sufficiently large. TSAY\((p)\), NN\((p)\) and HM\((p)\) can be very powerful in detecting some DGPs but may have little power against others even when the sample size increases.

4. The heteroscedasticity-robust generalized spectral test has similar power to the homoscedasticity-specific generalized spectral tests in most cases. However, there exist cases (bilinear (1) and nonlinear MA(1)) where the former is less powerful than the latter tests.

8. PREDICTABILITY AND NONLINEARITY OF STOCK RETURNS

We now use our tests to check the predictability of stock returns. Although several seemingly anomalous departures from market efficiency have been well documented, many financial economists still believe that no other proposition in economics has more solid empirical support than the efficient market hypothesis (EMH). The majority of studies on EMH has focused on the predictability of common stock returns. Using the variance ratio test, which is robust to conditional heteroscedasticity,\(^{21}\) Lo and MacKinlay (1988) found significant positive serial correlation for weekly and monthly stock returns.

It has been argued in the literature that significant autocorrelation in stock returns may be superficial: because small capitalization stocks trade less frequently than large stocks, new information is impounded first into large capitalization stock prices and then into small capitalization stock prices with a time lag. This time lag will induce a positive serial correlation in the weighted index of stock returns. Thus, the rejection of EMH for stock prices using autocorrelation may be the result of this nonsynchronous phenomenon. Using a hypothesized model, Lo and MacKinlay (1988) showed that nonsynchronous trading can at most account for part of the documented positive autocorrelation and concluded that stock returns are predictable. However, this model has not been empirically tested. Furthermore, Boudoukh, Richardson and Whitelaw (1994) showed that inferences from nonsynchronous trading models are highly sensitive to the assumptions on nontrading intervals and other stock market parameters, and they argued that prior studies understated the effects of nonsynchronous trading. It seems difficult to quantify how much of the significant autocorrelation could be attributed to nonsynchronous trading.

Here, we further contribute to this literature by taking a new approach. Instead of arguing how much the significant autocorrelation can be explained by nonsynchronous trading, we check whether stock returns are still predictable after removing all linear serial correlation. In other words, we check whether there exist predictable nonlinear components in mean. Lo and

\(^{21}\) The variance-ratio test can be interpreted as a test based on the power spectral density estimator at frequency zero, using the Bartlett kernel. See, e.g. Cochrane (1988).
MacKinlay's (1988) variance ratio test cannot be used for this purpose, because it can only capture linear dependence.

We consider two daily stock price indices: S&P 500 index and NASDAQ index, from 1 December 1972 to 31 December 2001, obtained from CRSP. Define stock return $Y_t = 100 \ln(P_t/P_{t-1})$, where $P_t$ is the closing stock price index at day $t$. A graphical examination shows strong volatility clustering for both returns series. Thus the heteroscedasticity-robust test $M_1(\hat{p}_0)$ should be used.

We first use $M_1(\hat{p}_0)$ to test whether the stock return series $\{Y_t\}$ is a m.d.s. Table 3, under subtitle “martingale testing”, reports the $M_1(\hat{p}_0)$ statistics using the data-driven lag order $\hat{p}_0$ in (6.4), with the preliminary bandwidth $\tilde{p} = c(10T)^{1/5}$, for $c = 1, \ldots, 10$. These statistics are quite robust to the choice of $\tilde{p}$ and have essentially zero asymptotic $p$-values, suggesting strong evidence against EMH for both S&P 500 and NASDAQ daily returns. Figure 1(a, b) displays the shapes of the supremum generalized spectral derivative modulus $m(\omega)$ in (3.5) for both S&P 500 and NASDAQ returns. They are apparently nonuniform over the frequency $\omega$, confirming the nonmartingale behaviour of stock prices. In particular, there exists more persistent serial dependence in mean for NASDAQ daily returns than for S&P 500 returns, because NASDAQ returns have a sharp mode in $m(\omega)$ at frequency zero.

Next, we examine whether stock returns contain predictable nonlinearities in mean after removing linear dependence. This checks if stock returns are linear in mean. We first estimate an AR($d$) model

$$Y_t = \alpha_0 + \sum_{j=1}^{d} \alpha_j Y_{t-j} + \epsilon_t,$$

where lag order $d$ is selected via the BIC criterion, which delivers a consistent order selection for stationary linear processes (Hannan, 1980). The selected models are an AR(2) for S&P 500, and an AR(1) for NASDAQ, with small but significant AR coefficients.\[22\] Table 3, under the

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**Table 3**

<table>
<thead>
<tr>
<th>$M_1(\hat{p}_0)$</th>
<th>Martingale testing</th>
<th>Linearity testing</th>
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<tr>
<td></td>
<td>S&amp;P 500</td>
<td>NASDAQ</td>
</tr>
<tr>
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<td>$p$-value</td>
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</table>

**Notes:** (1) The sample period for both S&P 500 and NASDAQ daily returns is from 1 December 1972 to 31 December 2001; (2) Martingale testing is the application of $M_1(\hat{p})$ to the raw stock returns $Y_t = 100 \ln(P_t/P_{t-1})$ where $P_t$ is the stock price at day $t$; (3) Linearity testing is the application of $M_1(\hat{p})$ to the estimated residuals of a linear AR($d$) model with intercept, where the order $d$ is selected by the BIC criterion. For S&P 500, the selected linear model is AR(2); for NASDAQ, the selected linear model is AR(1); (4) The data driven lag order $\hat{p}_0$ is computed using formula (6.4), with the preliminary bandwidth $\tilde{p} = c(10T)^{1/5}$, where $c$ ranges from 1 to 10.
subtitle “linearity testing”, reports the $\hat{M}_1(\hat{\rho}_0)$ statistics applied to the OLS AR($d$) residuals. These statistic values are much smaller than the $\hat{M}_1(\hat{\rho}_0)$ statistics applied to the raw return data, but they are still significant. The asymptotic $p$-values are below 2 for S&P 500 and are essentially zero for NASDAQ. These results suggest that stock returns contain predictable nonlinearities in mean, and the evidence is stronger for NASDAQ than S&P 500. Again, Figure 1(c, d) displays the shapes of the supremum generalized spectral derivative modulus $m(\omega)$ for two residual series, which are still nonuniform over $\omega$. Still, NASDAQ return residuals have a sharp mode for $m(\omega)$ at frequency zero, indicating that there exists more persistent nonlinear dependence in mean for NASDAQ daily returns than for S&P 500 daily returns. Interestingly, Figure 1 shows that there are two mild spectral modes at around $\omega = 0.6$ and 1.2 for both stock returns and their residuals. These correspond to some mild cyclical dynamics with periodicities of about 12 days and 6 days, respectively, which might be due to the well-known “calendar effects”.

The $\hat{M}_1(\hat{\rho}_0)$ test statistics obtained are very close to those under the AR($d$) specification.
9. CONCLUSION

Using a generalized spectral derivative approach, we develop a class of residual-based, generally applicable specification tests for linear and nonlinear conditional mean models in time series, where the dimension of the conditioning information set may be infinite. The tests can detect a wide range of model misspecification in mean while being robust to conditional heteroscedasticity and other higher order time-varying moments of unknown form. They check a large number of lags but naturally discount higher order lags, which alleviates the power loss due to the loss of a large number of degrees of freedom. The tests enjoy the appealing "nuisance parameter free" property that parameter estimation uncertainty has no impact on the limit distribution of the tests. A simulation study shows that it is important to take into account the impact of conditional heteroscedasticity to ensure a proper level. The tests have omnibus and robust power against a variety of dynamic misspecification and nonlinear alternatives in mean relative to some existing tests. We use our tests to check the predictability of stock price changes. After removing significant but possibly spurious autocorrelations due to nonsynchronous trading, we still find significant nonlinearity in mean for S&P 500 and NASDAQ daily returns.

MATHEMATICAL APPENDIX

Throughout the Appendix, we let $M_a(p)$, $a = 1, 2, 3$, be defined in the same way as $\hat{M}_a(p)$ in (3.11)–(3.13), with the unobservable sample $\{\epsilon_t = \xi_t(0)\}_{t=1}^T$, where $\theta_0 = \lim \hat{\theta}$, replacing the estimated residual sample $\{\hat{\epsilon}_t\}_{t=1}^T$ defined in (3.7). Also, $C \in (1, \infty)$ denotes a generic bounded constant.

**Proof of Theorem 1.** For space, we only consider $\hat{M}_1(p)$; the proofs for $\hat{M}_2(p)$ and $\hat{M}_3(p)$ are similar and a bit simpler. It suffices to show Theorems A1–A3 below. Theorem A1 implies that the use of $\{\hat{\epsilon}_t\}_{t=1}^T$ rather than $\{\epsilon_t\}_{t=1}^T$ has no impact on the limit distribution of $\hat{M}_1(p)$. Theorem A2 implies that the use of the truncated disturbances $\{\epsilon_{q,t}\}_{t=1}^T$ rather than $\{\epsilon_t\}_{t=1}^T$ has no impact on the limit distribution of $\hat{M}_1(p)$ for $q$ sufficiently large. The assumption that $\epsilon_{q,t}$ is independent of $\{\epsilon_{r,j}\}_{r=0}^{\infty}$ when $q$ is large simplifies a great deal the proof of asymptotic normality of $\hat{M}_1(p)$.

**Theorem A1.** Under the conditions of Theorem 1, $\hat{M}_1(p) - M_1(p) \overset{p}{\rightarrow} 0$.

**Theorem A2.** Let $M_{1q}(p)$ be defined as $M_1(p)$ with $\{\epsilon_{q,t}\}_{t=1}^T$ replacing $\{\epsilon_t\}_{t=1}^T$, where $\epsilon_{q,t}$ is as in Assumption A2. Then under the conditions of Theorem 1 and $q = p^{1 + \frac{1}{2} \log T}$, $M_{1q}(p) - M_1(p) \overset{p}{\rightarrow} 0$.

**Theorem A3.** Under the conditions of Theorem 1 and $q = p^{1 + \frac{1}{2} \log T}$, $M_{1q}(p) \overset{d}{\rightarrow} N(0, 1)$.

**Proof of Theorem A1.** Noting that $\epsilon_t(\theta) = Y_t - g(I_{t-1}, \theta)$ in (3.1), where $I_{t-1}$ is the unobservable information set from period $t$ to the infinite past, we write $\hat{\epsilon}_t = Y_t - g(I_{t-1}, \hat{\theta}) = \epsilon_t(\hat{\theta}) + g(I_{t-1}, \hat{\theta}) - g(I_{t-1}, \hat{\theta})$. Note that $\hat{\epsilon}_t \neq \epsilon_t(\hat{\theta})$ because $I_{t-1} \neq I_{t-1}$ generally, and Assumption A5 implies

$$\sum_{t=1}^T [\hat{\epsilon}_t - \epsilon_t(\hat{\theta})]^2 = \sum_{t=1}^T |g(I_{t-1}, \hat{\theta}) - g(I_{t-1}, \hat{\theta})|^2 = O_p(1). \tag{A.1}$$

By the mean value theorem, we have $\epsilon_t(\hat{\theta}) = \epsilon_t(\hat{\theta}) - g(I_{t-1}, \hat{\theta})$ for some $\hat{\theta}$ between $\hat{\theta}$ and $\hat{\theta}_0$, where $g_t(\theta) = \frac{\partial}{\partial \theta} g(I_{t-1}, \theta)$. It follows from the Cauchy–Schwarz inequality, and Assumptions A3 and A4 that

$$\sum_{t=1}^T |\epsilon_t(\hat{\theta}) - \epsilon_t|^2 \leq T \|\hat{\theta} - \theta_0\|^2 T^{-1} \sum_{t=1}^T \sup_{\theta \in \Theta_0} \|g_t(\theta)\|^2 = O_p(1), \tag{A.2}$$

where $\Theta_0$ is a neighbourhood of $\theta_0$. Both (A.1) and (A.2) imply

$$\sum_{t=1}^T (\hat{\epsilon}_t - \epsilon_t)^2 = O_p(1). \tag{A.3}$$
Now, put $T_j = T - |j|$, and let $\hat{\sigma}_j^{(1,0)}(0, v)$ be defined in the same way as $\hat{\sigma}_j^{(1,0)}(0, v)$ in (3.8), with $[\epsilon_t]_{t=1}^T$ replacing $[\bar{\epsilon}_t]_{t=1}^T$. To show $\hat{M}_t(p) - M_t(p) \overset{p}{\rightarrow} 0$, it suffices to show

$$\hat{D}_1^{(1,0)}(p) = \frac{1}{2} \left( \sum_{j=1}^{T-1} k^2(\bar{j}/p)T_j \left| \hat{\sigma}_j^{(1,0)}(0, v) \right|^2 - |\hat{\sigma}_j^{(1,0)}(0, v)|^2 \right) \overset{p}{\rightarrow} 0,$$

(A.4)

$\hat{C}_1(p) - \hat{C}_1(p) = O_p(T^{-\frac{1}{2}})$, and $\hat{D}_1(p) - D_1(p) \overset{p}{\rightarrow} 0$, where $\hat{C}_1(p)$ and $C_1(1)$ are defined in the same way as $\hat{C}_1(p)$ and $C_1(1)$ in (3.11), with $[\epsilon_t]_{t=1}^T$ replacing $[\bar{\epsilon}_t]_{t=1}^T$. For space, we focus on the proof of (A.4); the proofs for $\hat{C}_1(p) - \hat{C}_1(p) = O_p(T^{-\frac{1}{2}})$ and $\hat{D}_1(p) - D_1(p) \overset{p}{\rightarrow} 0$ are straightforward. We note that it is necessary to obtain the convergence rate $O_p(T^{-\frac{1}{2}})$ for $\hat{C}_1(p) - \hat{C}_1(p)$ to ensure that replacing $\hat{C}_1(p)$ with $\hat{C}_1(p)$ has asymptotically negligible impact given $p/T \to 0$.

To show (A.4), we first decompose

$$\int \sum_{j=1}^{T-1} k^2(\bar{j}/p)T_j \left| \hat{\sigma}_j^{(1,0)}(0, v) \right|^2 - |\hat{\sigma}_j^{(1,0)}(0, v)|^2 dW(v) = \hat{A}_1 + 2\text{Re}(\hat{A}_2),$$

(A.5)

where

$$\hat{A}_1 = \int \sum_{j=1}^{T-1} k^2(\bar{j}/p)T_j \left[ \hat{\sigma}_j^{(1,0)}(0, v) - \hat{\sigma}_j^{(1,0)}(0, v) \right] dW(v),$$

$$\hat{A}_2 = \int \sum_{j=1}^{T-1} k^2(\bar{j}/p)T_j \left[ \hat{\sigma}_j^{(1,0)}(0, v) - \hat{\sigma}_j^{(1,0)}(0, v) \right] \hat{\sigma}_j^{(1,0)}(0, v)^* dW(v),$$

where $\text{Re}(\hat{A}_2)$ is the real part of $\hat{A}_2$ and $\hat{\sigma}_j^{(1,0)}(0, v)^*$ is the complex conjugate of $\hat{\sigma}_j^{(1,0)}(0, v)$. Then, (A.4) follows from Propositions A1 and A2 below, and $p \to \infty$ as $T \to \infty$.

**Proposition A1.** Under the conditions of Theorem 1, $\hat{A}_1 = O_P(1)$.

**Proposition A2.** Under the conditions of Theorem 1, $p^{-\frac{1}{2}} \hat{A}_2 \overset{p}{\rightarrow} 0$.

**Proof of Proposition A1.** Put $\hat{\delta}^{(1,0)}(v) \equiv E(\hat{\delta}^{(1,0)}(v))$ and $\psi(v) \equiv E(\hat{\sigma}^{(1,0)}(v))$. Then straightforward algebra yields that for $j > 0$,

$$\hat{\sigma}_j^{(1,0)}(0, v) - \hat{\sigma}_j^{(1,0)}(0, v) = i \sum_{t=j+1}^{T-1} (\bar{\epsilon}_t - \epsilon_t) \hat{\delta}^{(1,0)}_{t-j}(v) - i \left[ \sum_{t=j+1}^{T-1} (\bar{\epsilon}_t - \epsilon_t) \hat{\delta}^{(1,0)}_{t-j}(v) \right]$$

$$- i \left[ \sum_{t=j+1}^{T-1} \psi^{(1,0)}_{t-j}(v) \right],$$

which we replace with $i \hat{\delta}^{(1,0)}_{t-j}(v) - \hat{\delta}^{(1,0)}_{t-j}(v) - i \psi^{(1,0)}_{t-j}(v)$. It follows that

$$\hat{A}_1 \leq 8 \sum_{a=1}^{6} \sum_{j=1}^{T-1} k^2(\bar{j}/p)T_j \left| \hat{B}_a(v) \right|^2 dW(v).$$

**Lemma A1.** $\sum_{j=1}^{T-1} k^2(\bar{j}/p)T_j \left| \hat{B}_1(v) \right|^2 dW(v) = O_P(p/T)$.

**Lemma A2.** $\sum_{j=1}^{T-1} k^2(\bar{j}/p)T_j \left| \hat{B}_2(v) \right|^2 dW(v) = O_P(p/T)$.

**Lemma A3.** $\sum_{j=1}^{T-1} k^2(\bar{j}/p)T_j \left| \hat{B}_3(v) \right|^2 dW(v) = O_P(p/T)$.

**Lemma A4.** $\sum_{j=1}^{T-1} k^2(\bar{j}/p)T_j \left| \hat{B}_4(v) \right|^2 dW(v) = O_P(p/T)$. **Proposition A1 follows from Lemmas A1 to A6 below, and $p/T \to 0$.**
Lemma A5. \[ \sum_{j=1}^{T-1} k^2(j/p)T_j \int |\hat{B}_{3j}(v)|^2 dW(v) = O_P(1). \]

Lemma A6. \[ \sum_{j=1}^{T-1} k^2(j/p)T_j \int |\hat{B}_{6j}(v)|^2 dW(v) = O_P(p/T). \]

We now show these lemmas. Throughout, we put \( a_T(j) \equiv k^2(j/p)T_j^{-1} \).

**Proof of Lemma A1.** By the Cauchy–Schwarz inequality and the inequality that \( |e^{iz_1} - e^{iz_2}| \leq |z_1 - z_2| \) for any real-valued variables \( z_1 \) and \( z_2 \), we have

\[ |\hat{B}_{1j}(v)|^2 \leq \left[ \sum_{t=1}^{T} (\hat{\epsilon}_t - \epsilon_t)^2 \right] \left[ \sum_{t=1}^{T} |\hat{\delta}_t(v)|^2 \right] \leq v^2 \left[ \sum_{t=1}^{T} (\hat{\epsilon}_t - \epsilon_t)^2 \right]. \]

It follows from (A.3), and Assumptions A6 and A7 that

\[ \int \sum_{j=1}^{T-1} k^2(j/p)T_j |\hat{B}_{1j}(v)|^2 dW(v) \leq \sum_{j=1}^{T-1} k^2(j/p)T_j^{-1} \int v^2 dW(v) = O_P(p/T), \]

where we made use of the fact that

\[ \sum_{j=1}^{T-1} a_T(j) = \sum_{j=1}^{T-1} k^2(j/p)T_j^{-1} = O(p/T) \] (A.7)

given \( p = cT^k \) for \( k \in (0, \frac{1}{2}) \), as shown in Hong (1999, A.15, p.1213).

**Proof of Lemma A2.** By the inequality that \( |e^{iz_1} - e^{iz_2}| \leq |z_1 - z_2| \) for any real-valued \( z_1 \) and \( z_2 \), we have

\[ |\hat{B}_{2j}(v)|^2 \leq \left[ \sum_{t=1}^{T} (\hat{\epsilon}_t - \epsilon_t)^2 \right] \left[ \sum_{t=1}^{T} |\hat{\delta}_t(v)|^2 \right] \leq v^2 \left[ \sum_{t=1}^{T} (\hat{\epsilon}_t - \epsilon_t)^2 \right]. \]

The desired result then follows using reasoning similar to that of Lemma A1.

**Proof of Lemma A3.** We decompose

\[ \hat{B}_{3j}(v) = T_j^{-1} \sum_{t=1}^{T} \epsilon_t e^{i\hat{\epsilon}_t(v) - \epsilon_t(v)} + T_j^{-1} \sum_{t=1}^{T} \epsilon_t e^{i\hat{\epsilon}_t(v) - \epsilon_t(v)} = \hat{B}_{31j}(v) + \hat{B}_{32j}(v). \] (A.8)

First, we consider \( \hat{B}_{31j}(v) \). Using the inequality that \( |e^{iz_1} - e^{iz_2}| \leq |z_1 - z_2| \) for any real-valued \( z_1 \) and \( z_2 \), Minkowski’s inequality, and the Cauchy–Schwarz inequality, we have

\[ E|\hat{B}_{31j}(v)|^2 \leq v^2 E \left[ \sum_{t=1}^{T} |\epsilon_t| (\hat{\epsilon}_t - \epsilon_t(v)) \right] \]

\[ \leq v^2 \left[ T_j^{-1} \sum_{t=1}^{T} (E\epsilon_t^2)^{1/4} \right] \left[ E\sup_{\theta \in \Theta} |g(I_{t-j}, \theta) - g(I_{t-j}, \theta)| \right] \]

\[ \leq CT_j^{1/2} v^2 \left[ \sum_{t=1}^{T} \sup_{\theta \in \Theta} |g(I_{t-j}, \theta) - g(I_{t-j}, \theta)| \right] \] (A.9)

It follows from Markov’s inequality, (A.7), and Assumptions A1, A5 and A7 that

\[ \sum_{j=1}^{T-1} k^2(j/p)T_j |\hat{B}_{31j}(v)|^2 = O_P(p/T). \]

Next, we consider \( \hat{B}_{32j}(v) \). Using the inequality that \( |e^{iz} - 1 - iz| \leq |z|^2 \) for any real-valued \( z \), we have

\[ |e^{i\epsilon_{t-j}(\theta)} - e^{i\epsilon_{t-j}(\hat{\theta})} - i\epsilon_{t-j}(\hat{\theta})| \leq v^2 |\epsilon_{t-j}(\hat{\theta}) - \epsilon_{t-j}|. \] (A.10)

Also, a second order Taylor series expansion yields

\[ \epsilon_{t-j}(\hat{\theta}) = \epsilon_{t-j} - g_{\epsilon_{t-j}}(\theta') (\hat{\theta} - \theta) - \frac{1}{2} (\hat{\theta} - \theta) g''_{\epsilon_{t-j}}(\theta')(\hat{\theta} - \theta) \] (A.11)

for some \( \hat{\theta} \) between \( \hat{\theta} \) and \( \theta \) where \( g''_{\epsilon_{t-j}}(\theta) = \frac{\partial^2}{\partial \theta^2} g(I_{t-j}, \theta) \). Put \( \tilde{\epsilon}_{t-j}(v) = g'_{\epsilon_{t-j}}(\theta) e^{i\epsilon_{t-j}} \). Then (A.10) and (A.11) imply

\[ |e^{i\epsilon_{t-j}(\hat{\theta})} - e^{i\epsilon_{t-j}(\hat{\theta})} - i\epsilon_{t-j}(\hat{\theta})| \leq v^2 |\epsilon_{t-j}(\hat{\theta}) - \epsilon_{t-j}|^2 + |v||\hat{\theta} - \theta||^2 \sup_{\theta \in \Theta} \|g''_{\epsilon_{t-j}}(\theta)\|. \]
Therefore, by the definition of \( \hat{B}_{32j}(v) \), we obtain

\[
T_j |\hat{B}_{32j}(v)| \leq |v||\hat{\theta} - \theta_0|| \left| \sum_{t=j+1}^{T} \epsilon_t \xi_{t-j}(v) \right| + v^2 \sum_{t=j+1}^{T} |\epsilon_t| |\xi_{t-j}(\hat{\theta}) - \xi_{t-j}|^2 \\
+ |v||\hat{\theta} - \theta_0|| \sum_{t=j+1}^{T} |\epsilon_t| \sup_{\theta \in \Theta_0} \|g''_{t-j}(\theta)\|.
\]

It follows from Assumptions A1 to A8 and (A.7) that

\[
\sum_{j=1}^{T-1} k^2(j/p) T_j |\hat{B}_{32j}(v)|^2 dW(v) \leq 4\| \sqrt{T}(\hat{\theta} - \theta_0) \|^2 \sum_{j=1}^{T-1} k^2(j/p) \\
\times \int \left( T_j^{-1} \sum_{t=j+1}^{T} \epsilon_t \xi_{t-j}(v) \right)^2 v^2 dW(v) + 4\| \sqrt{T}(\hat{\theta} - \theta_0) \|^4 \\
\times \left( \sum_{t=1}^{T-1} \epsilon_t^2 \right) \left( \sum_{t=1}^{T-1} \sup_{\theta \in \Theta_0} \|g''_{t}(\theta)\|^2 \right) \\
\times \left( \sum_{t=1}^{T-1} a_T(j) \right) \int v^2 dW(v) \\
= O_p(p/T), \quad (A.12)
\]

where we made use of the fact that \( E \| \sum_{t=j+1}^{T} \epsilon_t \xi_{t-j}(v) \|^2 \leq CT_j \) given \( E(\epsilon_t I_{t-1}) = 0 \) a.s. under \( \Theta_0 \) and Assumptions A1 and A3. The desired result of Lemma A5 follows from (A.8), (A.9) and (A.12).

**Proof of Lemma A4.** By the Cauchy–Schwarz inequality, \( |\hat{B}_{4j}(v)|^2 \leq (T_j^{-1} \sum_{t=j+1}^{T} \epsilon_t^2) T_j^{-1} \sum_{t=j+1}^{T} |\hat{\epsilon}_t(v)|^2 \). It follows from the Cauchy–Schwarz inequality, and \( |\hat{\epsilon}_t(v)| \leq |v| \cdot |\hat{\epsilon}_t - \epsilon_t| \) that

\[
\sum_{j=1}^{T-1} k^2(j/p) T_j \int |\hat{B}_{4j}(v)|^2 dW(v) \leq \sum_{j=1}^{T-1} k^2(j/p) \left( T_j^{-1} \sum_{t=j+1}^{T} \epsilon_t^2 \right) \left( \sum_{t=1}^{T-1} (\hat{\epsilon}_t - \epsilon_t)^2 \right) \int v^2 dW(v) = O_p(p/T),
\]

given (A.3) and (A.7), and \( E(\sum_{t=j+1}^{T} \epsilon_t^2) = \sigma^2 T_j \) by the m.d.s. hypothesis of \( \{\epsilon_t\} \).

**Proof of Lemma A5.** We first write

\[
\hat{B}_{5j}(v) = T_j^{-1} \sum_{t=j+1}^{T} [\hat{\epsilon}_{t-j}(\hat{\theta})] \psi_{t-j}(v) + \sum_{t=j+1}^{T} [\epsilon_t(\hat{\theta}) - \epsilon_t] \psi_{t-j}(v) = \hat{B}_{51j}(v) + \hat{B}_{52j}(v), \quad (A.13)
\]

Given \( |\psi_t(v)| \leq 2 \), (A.7), and Assumptions A5–A7, we have

\[
\sum_{j=1}^{T-1} k^2(j/p) T_j \int |\hat{B}_{5j}(v)|^2 dW(v) \leq 4 \sum_{t=1}^{T-1} [\hat{\epsilon}_t - \epsilon_t(\hat{\theta})]^2 \sum_{j=1}^{T-1} a_T(j) \int dW(v) = O_p(p/T), \quad (A.14)
\]

Also, by the second order Taylor series expansion in (A.11), we have

\[
-\hat{B}_{52j}(v) = (\hat{\theta} - \theta_0) T_j^{-1} \sum_{t=j+1}^{T} g''_{t}(\hat{\theta}) \psi_{t-j}(v) + \frac{1}{2}(\hat{\theta} - \theta_0)^2 \left[ T_j^{-1} \sum_{t=j+1}^{T} g''_{t}(\hat{\theta}) \psi_{t-j}(v) \right] (\hat{\theta} - \theta_0) \]

where \( \hat{\theta} \) lies between \( \hat{\theta} \) and \( \theta_0 \). Thus, we have

\[
\sum_{j=1}^{T-1} k^2(j/p) T_j \int |\hat{B}_{52j}(v)|^2 dW(v) \leq 2\| \sqrt{T}(\hat{\theta} - \theta_0) \|^2 \sum_{j=1}^{T-1} k^2(j/p) \\
\times \int \left( T_j^{-1} \sum_{t=j+1}^{T} g''_{t}(\hat{\theta}) \psi_{t-j}(v) \right)^2 dW(v) \\
+ 2 \| \sqrt{T}(\hat{\theta} - \theta_0) \|^4 \left[ T_j^{-1} \sum_{t=1}^{T-1} \sup_{\theta \in \Theta_0} \|g''_{t}(\theta)\|^2 \right] \int dW(v) = O_p(1) + O_p(p/T), \quad (A.15)
\]

where the last term is \( O_p(p/T) \) given (A.7), and the first term is \( O_p(1) \), as is shown below.
Put \( \eta_j(v) = E[g_j^t(\theta_0)^T \psi_{t-j}(v)] = \text{cov}[g_j^t(\theta_0), \psi_{t-j}(v)]. \) Then \( \sup_{v \in \mathbb{R}} \sum_{j=1}^{\infty} \| \eta_j(v) \| \leq C \) by Assumption A8. Next, expressing the moments by cumulants via well-known formulas (e.g. Hannan, 1970, (5.1), p. 23, for real-valued processes), we can obtain

\[
T_j E \left[ T_j^{-1} \sum_{t=j+1}^{T} g_j^t(\theta_0)^T \psi_{t-j}(v) - \eta_j(v) \right]^2 \leq \sum_{t=-T_j}^{T_j} \| \text{cov}[g_j^t(\theta_0), g_j^t(\theta_0)] \| \cdot \| \sigma_t(v, -v) \| + \sum_{t=-T_j}^{T_j} \| \eta_j + \sigma_t(v) \| \cdot \| \eta_j - \sigma_t(v) \| + \sum_{t=-T_j}^{T_j} \| \kappa_j, t, j + \sigma_t(v) \| \leq C, \tag{A.16}
\]

given Assumption A8, where \( \kappa_j, t, z(v) \) is as in Assumption A8. See also (A.7) of Hong (1999, p. 1212). Consequently, from (A.7) and (A.16), \( |k(\cdot)| \leq 1 \) and \( p/T \to 0 \), we have

\[
\sum_{j=1}^{T-1} k^2(j/p) \int \left| T_j^{-1} \sum_{t=j+1}^{T} g_j^t(\theta_0)^T \psi_{t-j}(v) \right|^2 dW(v) \leq C \sum_{j=1}^{T-1} \int \| \eta_j(v) \|^2 dW(v) + C \sum_{j=1}^{T-1} \sigma_T(j) = O(1) + O(p/T) = O(1).
\]

Hence the first term in (A.15) is \( O_P(1) \). The desired result of Lemma A5 follows from (A.13) to (A.15).

Proof of Lemma A1. The proof is analogous to that of Lemma A4.

Proof of Proposition A2. Given the decomposition in (A.6), we have

\[
|\tilde{\sigma}_j^{(1,0)}(0, v) - \tilde{\sigma}_j^{(1,0)}(0, v)| = \sum_{a=1}^{d} |\tilde{B}_{aj}(v)| |\tilde{\sigma}_j^{(1,0)}(0, v)|, \tag{A.17}
\]

where the \( \tilde{B}_{aj}(v) \) are defined in (A6). By the Cauchy–Schwarz inequality, we have

\[
\sum_{j=1}^{T-1} k^2(j/p) T_j \int |\tilde{B}_{aj}(v)||\tilde{\sigma}_j^{(1,0)}(0, v)| dW(v) \leq \left[ \sum_{j=1}^{T-1} k^2(j/p) T_j \int |\tilde{B}_{aj}(v)|^2 dW(v) \right]^{\frac{1}{2}} \left[ \sum_{j=1}^{T-1} k^2(j/p) T_j \int |\tilde{\sigma}_j^{(1,0)}(0, v)|^2 dW(v) \right]^{\frac{1}{2}} = O_P(p^\frac{3}{4} T^\frac{1}{2}) = O_P(p^\frac{1}{4}), \quad a = 1, 2, 3, 4, 6, \tag{A.18}
\]

given Lemmas A1–A4 and A6, and \( p/T \to 0 \), where \( p^{-1} \sum_{j=1}^{T-1} k^2(j/p) T_j \int |\tilde{\sigma}_j^{(1,0)}(0, v)|^2 dW(v) = O_P(1) \) by Markov’s inequality, the m.d.s. hypothesis of \( \{\varepsilon_t\} \), and (A.7).

It remains to consider \( a = 5 \). By (A.13) and the triangular inequality, we have

\[
\sum_{j=1}^{T-1} k^2(j/p) T_j \int |\tilde{B}_{5j}(v)||\tilde{\sigma}_j^{(1,0)}(0, v)| dW(v) \leq \sum_{j=1}^{T-1} k^2(j/p) T_j \int |\tilde{B}_{5j}(v)||\tilde{\sigma}_j^{(1,0)}(0, v)| dW(v) + \sum_{j=1}^{T-1} k^2(j/p) T_j \int |\tilde{B}_{5j}(v)||\tilde{\sigma}_j^{(1,0)}(0, v)| dW(v) \times \int |\tilde{B}_{5j}(v)||\tilde{\sigma}_j^{(1,0)}(0, v)| dW(v). \tag{A.19}
\]

For the first term in (A.19), we have

\[
\sum_{j=1}^{T-1} k^2(j/p) T_j \int |\tilde{B}_{5j}(v)||\tilde{\sigma}_j^{(1,0)}(0, v)| dW(v) \leq 2 \left[ \sum_{t=1}^{T} \sup_{\theta \in \Theta_0} [g(t^t_{t-1}, \theta) - g(t^t_{t-1}, \theta)] \right] \times \sum_{j=1}^{T-1} k^2(j/p) T_j \int |\tilde{\sigma}_j^{(1,0)}(0, v)| dW(v) = O_P(p T^\frac{1}{2}), \tag{A.20}
\]
given Assumption A5, (A.7), and the m.d.s. property of \( \{\varepsilon_t\} \). For the second term in (A.19), we have

\[
\sum_{j=1}^{T-1} k^2(j/p)T_j \int |\hat{B}_{2j}(v)||\tilde{\sigma}_j^{(1,0)}(0, v)|dW(v) \leq \|\hat{\theta} - \theta_0\| \sum_{j=1}^{T-1} k^2(j/p)T_j
\]

\[
\times \left[ T_j^{-1} \sum_{j=1}^{T-1} \psi_j'(\theta_0)\psi_{j-1}(v) \right]^{1/2} \|\tilde{\sigma}_j^{(1,0)}(0, v)\|dW(v)
\]

\[
+ T \|\hat{\theta} - \theta_0\|^2 \left[ T_j^{-1} \sum_{j=1}^{T} \sup_{\theta \in \Theta_0} \|\psi_j'(\theta)\| \right]
\]

\[
\times \sum_{j=1}^{T-1} k^2(j/p) \int |\tilde{\sigma}_j^{(1,0)}(0, v)|dW(v)
\]

\[
= O_{p}(1 + p/T^{1/2}) + O_{p}(p/T^{1/2}) = o_{p}(p^{1/2})
\]

(A.21)

given \( p \to \infty, p/T \to 0 \), and Assumptions A3–A8, where we have made use of the fact that \( T_j E[|\tilde{\sigma}_j^{(1,0)}(0, v)|^2] \leq C \) under the m.d.s. hypothesis of \( \{\varepsilon_t\} \). Note that for the first term in (A.21), we have made use of the fact that

\[
E \left[ \left| T_j^{-1} \sum_{t=j+1}^{T} \psi_j'(\theta_0)\psi_{t-j}(v) \right| \right] \leq \left( \left[ E \left[ \left| T_j^{-1} \sum_{t=j+1}^{T} \psi_j'(\theta_0)\psi_{t-j}(v) \right|^2 \right] \right]^{1/2} \left[ E[|\tilde{\sigma}_j^{(1,0)}(0, v)|^2] \right]^{1/2}
\]

\[
\leq C[\|\eta_j(v)\| + CT_j^{-1/2}]T_j^{-1/2}
\]

by (A.16), and consequently,

\[
T_j^{-1/2} \sum_{t=j+1}^{T-1} k^2(j/p)T_jE \left[ \left| T_j^{-1} \sum_{t=j+1}^{T} \psi_j'(\theta_0)\psi_{t-j}(v) \right| \right] \leq C \sum_{j=1}^{T-1} \left[ \|\eta_j(v)\|dW(v) + CT_j^{-1/2} \sum_{t=j+1}^{T-1} k^2(j/p) \right] = O_{p}(1 + p/T^{1/2})
\]

given \( |k(\cdot)| \leq 1 \) and Assumption A8. Combining (A.19)–(A.21) then yields the result of this lemma. \( \square \)

Proof of Theorem A2. The proof is similar to that of Theorem A1. Let \( \hat{A}_{1q} \) and \( \hat{A}_{2q} \) be defined in the same way as \( \hat{A}_1 \) and \( \hat{A}_2 \) in (A.5), with \( [\varepsilon_{q,t}]_{t=1}^{T} \) replacing \( [\varepsilon_t]_{t=1}^{T} \). It suffices to show \( p^{-1/2} \hat{A}_{1q} \to^{P} 0 \) and \( p^{-1/2} \hat{A}_{2q} \to^{P} 0 \).

Put \( \delta_{q,t} = e^{i\varepsilon_{q,t}} - e^{i\varepsilon_{q,t}} \) and \( \varphi_{q,t}(v) \equiv e^{i\varepsilon_{q,t}} - \varphi_q(v) \), where \( \varphi_q(v) \equiv E(e^{i\varepsilon_{q,t}}) \). Let \( \delta_{q,j}^{(1,0)}(0, v) \) be defined as \( \delta_j^{(1,0)}(0, v) \), with \( [\varepsilon_{q,t}]_{t=1}^{T} \) replacing \( [\varepsilon_t]_{t=1}^{T} \). Then, similar to (A.6), we have

\[
\tilde{\delta}_j^{(1,0)}(0, v) \approx \tilde{\sigma}_j^{(1,0)}(0, v) = i T_j^{-1} \sum_{t=j+1}^{T} \left( \varepsilon_t - \varepsilon_{q,t} \right) \delta_{q,j-t}(v) - \left[ T_j^{-1} \sum_{t=j+1}^{T} \varepsilon_{q,t} \delta_{q,t-j}(v) \right]
\]

\[
\times \left[ T_j^{-1} \sum_{t=j+1}^{T} \psi_{t-j}(v) \right]^{1/2} \left[ T_j^{-1} \sum_{t=j+1}^{T} \psi_{t-j}(v) \right]^{1/2}
\]

\[
+ i T_j^{-1} \sum_{t=j+1}^{T} \left( \varepsilon_t - \varepsilon_{q,t} \right) \Psi_{q,t-j}(v) - i \left[ T_j^{-1} \sum_{t=j+1}^{T} \varepsilon_{q,t} \Psi_{q,j-t}(v) \right]
\]

\[
\times \left[ T_j^{-1} \sum_{t=j+1}^{T} \psi_{t-j}(v) \right]
\]

\[
= \{ \hat{B}_{1j}(v) - \hat{B}_{2j}(v) + \hat{B}_{3j}(v) + \hat{B}_{4j}(v) - \hat{B}_{5j}(v) + \hat{B}_{6j}(v) \}, \text{ say.}
\]

Following reasoning analogous to that of Theorem A1 and noting that \( E(\varepsilon_t | I_{t-1}) = 0 \) a.s. and \( E(\varepsilon_{q,t} | I_{t-1}) = 0 \) a.s., we obtain

\[
p^{-1/2} \hat{A}_{1q} \leq 8p^{-1/2} \sum_{a=1}^{6} \sum_{j=1}^{T-1} k^2(j/p)T_j \int |\hat{B}_{a,j}(v)|^2dW(v) = O_{p}(p^{1/2}/q^k) = o_{p}(1)
\]

given Assumption A2, \( q/p \to \infty \) and \( k \geq 1 \). Moreover, by the Cauchy–Schwartz inequality, we can obtain

\[
p^{-1/2} \hat{A}_{2q} = 2p^{-1/2} \sum_{a=1}^{6} \sum_{j=1}^{T-1} k^2(j/p)T_j \int |\hat{B}_{a,j}(v)|\tilde{\sigma}_j^{(1,0)}(0, v)|dW(v) = O_{p}(p^{1/2}/q^k) = o_{p}(1).
\]

This completes the proof of Theorem A2. \( \square \)
Proof of Theorem A3. We shall show Propositions A3 and A4 below.

Proposition A3. Let \( \tilde{\sigma}_{q,j}^{(1,0)}(0, v) \) be defined as \( \sigma_{j}^{(1,0)}(0, v) \), and let \( \tilde{\mathcal{C}}_{1q}(p) \) be defined as \( \mathcal{C}_{1}(p) \), with \( \{e_{q,t}\}_{t=1}^{T} \) replacing \( \{e_{q,1}\}_{t=1}^{T} \). Then under the conditions of Theorem 1,

\[
p^{-\frac{1}{2}} \sum_{j=1}^{T-1} k^{2}(j/p) T_{j} \int [\tilde{\sigma}_{q,j}^{(1,0)}(0, v)]^{2} dW(v) = p^{-\frac{1}{2}} \tilde{\mathcal{C}}_{1q}(p) + p^{-\frac{1}{2}} \tilde{\mathcal{V}}_{q} + o_{p}(1),
\]

where \( \tilde{\mathcal{V}}_{q} = \sum_{t=2q+2}^{T} e_{q,t} \sum_{j=1}^{q-2q+1} a_{T}(j) \int \psi_{q,t-j}(v) \sum_{s=1}^{t-2q+1} e_{q,s} \psi_{q,s-j}(v) dW(v) \).

Proof of Proposition A3. Recall that \( \tilde{\sigma}_{q,j}^{(1,0)}(0, v) = \mathcal{T}_{j}^{-1} \sum_{t=1}^{T} e_{q,t} \psi_{q,t}(v) \), where \( \psi_{q,t}(v) = e^{i\psi_{q,t}} - \phi_{q}(v) \) and \( \phi_{q}(v) = E(e^{i\psi_{q,t}}) \). We first decompose

\[
\sum_{j=1}^{T-1} k^{2}(j/p) T_{j} \int [\tilde{\sigma}_{q,j}^{(1,0)}(0, v)]^{2} dW(v) = \sum_{j=1}^{T-1} a_{T}(j) \int \left| \sum_{t=1}^{T} e_{q,t} \psi_{q,t-j}(v) \right|^{2} dW(v) + 2 \text{Re} \sum_{j=1}^{T-1} a_{T}(j) \int \left[ \sum_{t=1}^{T} e_{q,t} \psi_{q,t-j}(v) \right]^{*} dW(v) - 2 \text{Re} \sum_{j=1}^{T-1} a_{T}(j) \int \left[ \sum_{t=1}^{T} e_{q,t} \psi_{q,t-j}(v) \right]^{2} dW(v)
\]

Next we write

\[
\tilde{\mathcal{V}}_{q} = \sum_{t=2q+2}^{T} e_{q,t} \sum_{j=1}^{q-2q+1} a_{T}(j) \int \psi_{q,t-j}(v) \sum_{s=1}^{t-2q+1} e_{q,s} \psi_{q,s-j}(v) dW(v) + 2 \text{Re} \sum_{j=1}^{T-1} a_{T}(j) \int \left[ \sum_{t=1}^{T} e_{q,t} \psi_{q,t-j}(v) \right]^{*} dW(v)
\]

Proposition A4. Let \( \tilde{D}_{1q}(p) \) be defined as \( \tilde{D}_{1}(p) \) with \( \{e_{q,t}\} \) replacing \( \{e_{q,1}\} \). Then \( \tilde{D}_{1q}^{-1}(p) \tilde{V}_{q} \to N(0, 1) \).

Proof of Proposition A4. Recall that \( \tilde{\sigma}_{q,j}^{(1,0)}(0, v) = \mathcal{T}_{j}^{-1} \sum_{t=1}^{T} e_{q,t} \psi_{q,t}(v) \), where \( \psi_{q,t}(v) = e^{i\psi_{q,t}} - \phi_{q}(v) \) and \( \phi_{q}(v) = E(e^{i\psi_{q,t}}) \). We first decompose

\[
\sum_{j=1}^{T-1} k^{2}(j/p) T_{j} \int [\tilde{\sigma}_{q,j}^{(1,0)}(0, v)]^{2} dW(v) = \sum_{j=1}^{T-1} a_{T}(j) \int \left| \sum_{t=1}^{T} e_{q,t} \psi_{q,t-j}(v) \right|^{2} dW(v) + 2 \text{Re} \sum_{j=1}^{T-1} a_{T}(j) \int \left[ \sum_{t=1}^{T} e_{q,t} \psi_{q,t-j}(v) \right]^{*} dW(v) - 2 \text{Re} \sum_{j=1}^{T-1} a_{T}(j) \int \left[ \sum_{t=1}^{T} e_{q,t} \psi_{q,t-j}(v) \right]^{2} dW(v)
\]

where in the first term \( \tilde{U}_{1q} \), we have \( t - s > 2q \) so that \( \{e_{q,t} \psi_{q,t-j}(v)\}_{t=1}^{q} \) is independent of \( \{e_{q,s} \psi_{q,s-j}(v)\}_{s=1}^{q} \) for \( q \) sufficiently large. In the second term \( \tilde{R}_{3q} \), we have \( 0 < t - s < 2q \). Finally, we write

\[
\tilde{U}_{1q} = \sum_{t=2q+2}^{T} e_{q,t} \sum_{j=1}^{q-2q+1} a_{T}(j) \int \psi_{q,t-j}(v) \sum_{s=1}^{t-2q+1} e_{q,s} \psi_{q,s-j}(v) dW(v)
\]

\[
\tilde{V}_{q} = \sum_{t=1}^{T-1} k^{2}(j/p) T_{j} \int [\tilde{\sigma}_{q,j}^{(1,0)}(0, v)]^{2} dW(v) = \mathcal{C}_{q}(p) + 2 \text{Re} \mathcal{V}_{q} + 2 \text{Re} \tilde{U}_{1q} - 2 \text{Re} \tilde{R}_{3q} - \tilde{R}_{4q}.
\]
It suffices to show Lemmas A7–A11 below, which imply \( p^{-\frac{1}{2}}[\hat{C}_q(p) - \tilde{C}_1q(p)] = o_P(1) \) and \( p^{-\frac{1}{2}} \tilde{R}_{aq} = o_P(1) \) for \( a = 1, 2, 3, 4 \) given \( q = p^{1+\frac{1}{4b-2}}(\ln(T))^{2b-1} \) and \( p = cT^\lambda \) for \( 0 < \lambda < \left(3 + \frac{1}{4b-2}\right)^{-1} \).

**Lemma A7.** Let \( \hat{C}_q(p) \) be defined as in (A.23). Then \( \hat{C}_q(p) - \tilde{C}_1q(p) = o_P(p^2/T) \).

**Lemma A8.** Let \( \tilde{R}_{1q} \) be defined as in (A.22). Then \( \tilde{R}_{1q} = o_P(p^2/T) \).

**Lemma A9.** Let \( \tilde{R}_{2q} \) be defined as in (A.22). Then \( \tilde{R}_{2q} = o_P(p^2/T) \).

**Lemma A10.** Let \( \tilde{R}_{3q} \) be defined as in (A.24). Then \( \tilde{R}_{3q} = o_P(q^{1/2}/pT) \).

**Lemma A11.** Let \( \tilde{R}_{4q} \) be defined as in (A.25). Then \( \tilde{R}_{4q} = o_P(p^{2b}(T)/q^{4b-2}) \).

**Proof of Lemma A7.** By Markov’s inequality and \( E[\hat{C}_q(p) - \tilde{C}_1q(p)] \leq Cp^2/T \) given \( \sum_{j=1}^{T-1} (j/p)a_T(j) = O(p/T) \).

**Proof of Lemma A8.** By the m.d.s. property of \( \{q,t, F_{t-1}\} \) where \( F_{t-1} \) is the sigma-field generated by \( \left\{
abla t-j \right\}_{j=1}^{\infty} \), we can obtain \( E \int \left| \sum_{j=1}^{T} q_t \psi_{q,t-j}(v) \right|^2 dW(v) \leq \sum_{j=1}^{T} E \left| \sum_{i=1}^{T} q_t \psi_{q,t-j}(v) \right|^2 dW(v) \leq C(jT)^{1/2} \) given Assumption A6.

**Proof of Lemma A9.** The proof is similar to that of Lemma A8, with the fact that \( E \int \left| \sum_{j=1}^{T} q_t \psi_{q,t-j}(v) \right|^2 dW(v) \leq C(jT)^{1/2} \) given Assumption A6.

**Proof of Lemma A10.** By the m.d.s. property of \( \{q,t, F_{t-1}\} \), Minkowski’s inequality and (A.7), we have

\[
E[\tilde{R}_{3q}]^2 \leq \sum_{j=1}^{T-1} \left( \sum_{j=1}^{T-1} a_T(j) \int q_t \psi_{q,t-j}(v) \sum_{s=1}^{T-1} q_s \psi_{s,j}(v) dW(v) \right)^2 \leq 2CTq \sum_{j=1}^{T-1} a_T(j)^2 = O(qp^2/T).
\]

**Proof of Lemma A11.** By the m.d.s. property of \( \{q,t, F_{t-1}\} \) and Minkowski’s inequality, we have

\[
E[\tilde{R}_{4q}]^2 \leq \sum_{j=1}^{T} \left( \sum_{j=1}^{T} a_T(j) \int q_t \psi_{q,t-j}(v) \sum_{s=1}^{T-1} q_s \psi_{s,j}(v) dW(v) \right)^2 \leq \sum_{j=1}^{T} \left( \sum_{j=1}^{T} a_T(j) \int q_t \psi_{q,t-j}(v) \sum_{s=1}^{T-1} q_s \psi_{s,j}(v) dW(v) \right)^2 \leq \sum_{j=1}^{T} \left( \sum_{j=1}^{T} a_T(j) \right)^2 \leq C^2 T^2 \left( \sum_{j=1}^{T} (j/p)^{2b} T_j \right)^2 \leq C^2 T^2 \left( \sum_{j=1}^{T} (j/p)^{2b} T_j \right)^2 \leq C^2 T^2 \left( \sum_{j=1}^{T} (j/p)^{2b} T_j \right)^2 \leq C^2 T^2 \left( \sum_{j=1}^{T} (j/p)^{2b} T_j \right)^2 \leq O(p^{2b}(T)/q^{4b-2})
\]

given Assumption A6 (i.e. \( k(z) \leq C|z|^{-b} \) as \( z \to \infty \)).

**Proof of Proposition A4.** We rewrite \( \tilde{V}_q = \sum_{j=2q+1}^{T} q_t \), where

\[
V_q(t) = q_t \sum_{j=1}^{T} a_T(j) \int \psi_{q,t-j}(v) H_{j,t-2q-1}(v) dW(v).
\]
and \( H_{q,t-2q-1}(v) = \sum_{s=1}^{t-2q-1} \epsilon_{q,s} \psi_{s,t-j}(v) \). We apply the martingale limit theorem (Brown, 1971), which states 
\[
\text{var}(2 \text{Re} \tilde{V}_q)^{-1} 2 \text{Re} \tilde{V}_q \xrightarrow{d} \mathcal{N}(0, 1) \text{ if}
\]

\[
\text{var}(2 \text{Re} \tilde{V}_q)^{-1} \sum_{t=1}^{T} [2 \text{Re} V_q(t)]^2 1[|2 \text{Re} V_q(t)| > \eta \cdot \text{var}(2 \text{Re} \tilde{V}_q)^{1/2}] \to 0 \ \forall \eta > 0, \quad (A.26)
\]

\[
\text{var}(2 \text{Re} \tilde{V}_q)^{-1} \sum_{t=1}^{T} E \left[ 2 \text{Re} V_q^2(t) | \mathcal{F}_{t-1} \right] \xrightarrow{p} 1. \quad (A.27)
\]

First, we compute \( \text{var}(2 \text{Re} V_q) \). By the m.d.s. property of \( \{ \epsilon_{q,t}, \mathcal{F}_{t-1} \} \) under \( \mathcal{H}_0 \) and independence between \( \epsilon_{q,t} \) and \( \{ \eta_{l-j-1} \}_{q=1}^{\infty} \) for \( q \) sufficiently large, we have

\[
E(\tilde{V}_q^2) = \sum_{t=2q+2}^{T} E \left[ 2 \text{Re} \tilde{V}_q^2(t) \right] = \sum_{j=1}^{q} \sum_{l=1}^{q} a_T(j) a_T(l) \int \int \sum_{t=2q+2}^{T} \sum_{s=1}^{t-2q-1} \epsilon_{q,s} \psi_{s,t-j}(v) dW(v) \right]^2 
\]

\[
= \sum_{t=2q+2}^{T} E \left[ 2 \text{Re} \tilde{V}_q^2(t) | \mathcal{F}_{t-1} \right] \xrightarrow{p} 1. \quad (A.28)
\]

where we have made use of the fact that \( E[\epsilon_{q,t}^2 \psi_{q,-j}(v) \psi_{q,-l}(v')] = E[\epsilon_{q,t}^2 \psi_{q,-j}(v) \psi_{q,-l}(v')] \) as \( q \to \infty \) given Assumption A2. Put \( C(0, j, l) = E[(\sigma^2 - \sigma^2 \psi_{q,-j}(v) \psi_{q,-l}(v')] \). Then

\[
E(\epsilon_{q,t}^2 \psi_{q,-j}(v) \psi_{q,-l}(v')) = C(0, j, l) + \sigma^2 \sigma_{q,-j}(v, v'),
\]

\[
|E[\epsilon_{q,t}^2 \psi_{q,-j}(v) \psi_{q,-l}(v')]|^2 = |C(0, j, l)|^2 + \sigma^4 |\sigma_{q,-j}(v, v')|^2 + 2\sigma^2 \text{Re}[C(0, j, l) \sigma_{q,-j}(v, v')].
\]

Given \( \sum_{j=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} |C(0, j, l)| < \infty, \) and \( |k()| \leq 1, \) we have

\[
\text{var}(2 \text{Re} \tilde{V}_q) = 2\sigma^4 \sum_{j=1}^{q} \sum_{l=1}^{q} k^2(j/p) k^2(l/p) \int \int |\sigma_{q,-j}(v, v')|^2 dW(v) dW(v') [1 + o(1)]
\]

\[
= 2\sigma^4 p \sum_{m=1}^{q-1} \left[ p^{-1} \sum_{j=m+1}^{q} k^2(j/p) k^2[(j-m)/p] \right]
\]

\[
\times \int \int |\sigma_{m}(v, v')|^2 dW(v) dW(v') [1 + o(1)]
\]

\[
= 2\sigma^4 p \int_0^\infty k^4(z) \int \int |\sigma_{m}(v, v')|^2 dW(v) dW(v') [1 + o(1)]
\]

\[
= 4\pi \sigma^4 p \int_0^\infty k^4(z) \int \int |f(\omega, v', v')|^2 d\omega dW(v) dW(v') [1 + o(1)],
\]

where we used the fact that for any given \( m, p^{-1} \sum_{j=m+1}^{q} k^2(j/p) k^2[(j-m)/p] \to \int_0^\infty k^4(z) dz \) as \( p \to \infty, q/p \to 0. \)
We now verify condition (A.26). Noting that \( E[H_{j,t-2q-1}(v)]^4 \leq C_2^4 \) for \( 1 \leq j \leq q \) given the m.d.s. property of \( \{e_{q,t}, F_{t-1}\} \) and Rosenthal’s inequality (cf. Hall and Heyde, 1980, p. 23), we have

\[
E[V_q(t)]^4 \leq \left[ \sum_{j=1}^{q} a_T(j) \int \left( E \left[ e_{q,t} \varphi_{q,t-j}(v) H_{j,t-2q-1}(v) \right] \right)^4 dW(v) \right]^4 \\
\leq C_2^4 \left[ \sum_{j=1}^{q} a_T(j) \right]^4 = O(p^4 T^4).
\]

It follows that \( \sum_{t=2q+2}^{T} E[V_q(t)]^4 = O(p^4 T^4) = o(p^2) \) given \( p^2 / T \to 0 \). Thus, (A.26) holds.

Next, we verify condition (A.27). Put \( \sigma_{q,t}^2 = E[e_{q,t}^2 | F_{t-1}] \). Then

\[
E[V_q(t)^2 | F_{t-1}] = \sigma_{q,t}^2 \left[ \sum_{j=1}^{q} a_T(j) \int \varphi_{q,t-j}(v) H_{j,t-2q-1}(v) \right]^2 \\
= \sum_{j=1}^{q} \sum_{l=1}^{q} a_T(j)a_T(l) \int \sigma_{q,t}^2 \varphi_{q,t-j}(v) \varphi_{q,t-l}(v') \times H_{j,t-2q-1}(v) H_{l,t-2q-1}(v') dW(v) dW(v') \\
= \sum_{j=1}^{q} \sum_{l=1}^{q} a_T(j)a_T(l) \int \int \sigma_{q,t}^2 \varphi_{q,t-j}(v) \varphi_{q,t-l}(v') \times H_{j,t-2q-1}(v) H_{l,t-2q-1}(v') dW(v) dW(v') \\
+ \sum_{j=1}^{q} \sum_{l=1}^{q} a_T(j)a_T(l) \int \int \tilde{Z}_{q,t}^{j,l}(v,v') H_{j,t-2q-1}(v) H_{l,t-2q-1}(v') dW(v) dW(v') \\
= S_{1q}(t) + V_{1q}(t) \text{, say.} \quad (A.29)
\]

where \( \tilde{Z}_{q,t}^{j,l}(v,v') = \sigma_{q,t}^2 \varphi_{q,t-j}(v) \varphi_{q,t-l}(v') - E[\sigma_{q,t}^2 \varphi_{q,t-j}(v) \varphi_{q,t-l}(v')] \). We further decompose

\[
S_{1q}(t) = \sum_{j=1}^{q} \sum_{l=1}^{q} a_T(j)a_T(l) \int \sigma_{q,t}^2 \int \varphi_{q,t-j}(v) \varphi_{q,t-l}(v') \times H_{j,t-2q-1}(v) H_{l,t-2q-1}(v') dW(v) dW(v') \\
+ \sum_{j=1}^{q} \sum_{l=1}^{q} a_T(j)a_T(l) \int \sigma_{q,t}^2 \int \varphi_{q,t-j}(v) \varphi_{q,t-l}(v') \times \{H_{j,t-2q-1}(v) H_{l,t-2q-1}(v') - E[H_{j,t-2q-1}(v) H_{l,t-2q-1}(v')]\} dW(v) dW(v') \\
= E[V_q(t)^2] + S_{2q}(t) \text{, say.} \quad (A.30)
\]

where

\[
E[V_q(t)^2] = \sum_{j=1}^{q} \sum_{l=1}^{q} (t - q - 1)a_T(j)a_T(l) \int \sigma_{q,t}^2 \int \varphi_{q,t-j}(v) \varphi_{q,t-l}(v') \times H_{j,t-2q-1}(v) H_{l,t-2q-1}(v') dW(v) dW(v').
\]

Put \( Z_{q,t}^{j,l}(v,v') = e_{q,t}^2 \varphi_{q,t-j}(v) \varphi_{q,t-l}(v') - E[e_{q,t}^2 \varphi_{q,t-j}(v) \varphi_{q,t-l}(v')] \). Then we write

\[
S_{2q}(t) = \sum_{j=1}^{q} \sum_{l=1}^{q} a_T(j)a_T(l) \int \sigma_{q,t}^2 \int \varphi_{q,t-j}(v) \varphi_{q,t-l}(v') \times \int \int \tilde{Z}_{q,t}^{j,l}(v,v') H_{j,t-2q-1}(v) H_{l,t-2q-1}(v') dW(v) dW(v') \\
+ \sum_{j=1}^{q} \sum_{l=1}^{q} a_T(j)a_T(l) \int \sigma_{q,t}^2 \int \varphi_{q,t-j}(v) \varphi_{q,t-l}(v') \times \sum_{j=2}^{t-2q-1} \sum_{l=1}^{q} e_{q,t} \varphi_{q,t-j}(v) e_{q,t} \varphi_{q,t-l}(v') dW(v) dW(v') \\
= V_{2q}(t) + S_{3q}(t) \text{, say.} \quad (A.31)
\]

where

\[
S_{3q}(t) = \sum_{j=1}^{q} \sum_{l=1}^{q} a_T(j)a_T(l) \int \sigma_{q,t}^2 \int \varphi_{q,t-j}(v) \varphi_{q,t-l}(v') \\
\times \sum_{0 \leq s - r \leq 2q} \sum_{0 \leq s - r \leq 2q} e_{q,t} \varphi_{q,t-s}(v) e_{q,t} \varphi_{q,t-r}(v') dW(v) dW(v') \\
+ \sum_{j=1}^{q} \sum_{l=1}^{q} a_T(j)a_T(l) \int \sigma_{q,t}^2 \int \varphi_{q,t-j}(v) \varphi_{q,t-l}(v') \\
\times \sum_{0 \leq s - r \leq 2q} \sum_{0 \leq s - r \leq 2q} e_{q,t} \varphi_{q,t-s}(v) e_{q,t} \varphi_{q,t-r}(v') dW(v) dW(v') \\
= V_{3q}(t) + V_{4q}(t) \text{, say.} \quad (A.32)
\]
It follows from (A.29) to (A.32) that $\sum_{t=2q+2}^{T}[E[V_{q}^{2}(t)|F_{t-1}]-E[V_{q}^{2}(t)]] = \sum_{a=1}^{q} \sum_{t=2q+2}^{T} V_{aq}(t)$. It suffices to show Lemmas A12–A15 below, which imply $E[\sum_{t=2q+2}^{T}E[V_{q}^{2}(t)|F_{t-1}]-E[V_{q}^{2}(t)]^{2} = o(p^{2})$ given $q = p^{1+1/(\ln T)^{1-1}}$ and $p = cT^{\lambda}$ for $0 < \lambda < (3 + 1/(4\delta-2))^{-1}$. Thus, condition (A.27) holds, and so $M_{1,q}(p) \rightarrow N(0,1)$ by Brown’s theorem.

**Lemma A12.** Let $V_{1q}(t)$ be defined as in (A.29). Then $E[\sum_{t=2q+2}^{T} V_{1q}(t)]^{2} = O(qp^{4}/T)$.

**Lemma A13.** Let $V_{2q}(t)$ be defined as in (A.31). Then $E[\sum_{t=2q+2}^{T} V_{2q}(t)]^{2} = O(qp^{4}/T)$.

**Lemma A14.** Let $V_{3q}(t)$ be defined as in (A.32). Then $E[\sum_{t=2q+2}^{T} V_{3q}(t)]^{2} = O(qp^{4}/T)$.

**Lemma A15.** Let $V_{4q}(t)$ be defined as in (A.32). Then $E[\sum_{t=2q+2}^{T} V_{4q}(t)]^{2} = O(p)$.

**Proof of Lemma A12.** Recall the definition of $Z_{q,r}(v,v')$ as in (A.29). Noting that $Z_{q,r}(v,v')$ is independent of $\{H_{j,t-2q-1}(v)H_{l,t-2q-1}(v')\}$ and that $Z_{q,r}(v,v')$ is independent of $Z_{q,r}(v,v')$ for $t - \tau > 2q$ and $1 \leq j, l \leq q$, we can obtain

$$E \left[ \sum_{t=2q+2}^{T} Z_{q,r}(v,v')H_{j,t-2q-1}(v)H_{l,t-2q-1}(v') \right]^{2} \leq \sum_{[t-\tau] \leq 2q} \sum_{[t-\tau] \leq 2q} E[Z_{q,r}(v,v')Z_{q,r}(v,v')]$$

where we have made use of the fact that $E[H_{j,t-2q-1}(v)^{4}] \leq C\tau^{2}$ for $1 \leq j \leq q$. It follows by Minkowski’s inequality and (A.7) that

$$E \left[ \sum_{t=2q+2}^{T} V_{1q}(t) \right]^{2} \leq \sum_{j=1}^{q} \sum_{l=1}^{q} a_{T}(j)a_{T}(l) \left( E \left[ \sum_{t=2q+2}^{T} \int Z_{q,r}(v,v')H_{j,t-2q-1}(v)H_{l,t-2q-1}(v') dW dW' \right]^{2} \right)^{1/2}^{2} = o(qp^{4}/T).$$

**Proof of Lemma A13.** Recalling the definition of $Z_{q,r}(v,v')$ in (A.31) and noting that $\{Z_{q,r}(v,v')\}_{j,l=1}^{q}$ is independent of $\{Z_{q,r}(v,v')\}_{j,l=1}^{q}$ for $|s-\tau| > 2q$ where $q$ is sufficiently large, we have $E[\Sigma_{t=1}^{T} Z_{q,r}(v,v')]^{2} = \sum_{[s-\tau] \leq 2q} E[Z_{q,r}(v,v')Z_{q,r}(v,v')] \leq 2C\tau q$. It follows that

$$E \left[ \sum_{t=2q+2}^{T} V_{2q}(t) \right]^{2} \leq \sum_{t=2q+2}^{T} \left[ E[V_{2q}(t)]^{2} \right]^{1/2}^{2} \leq \sum_{t=2q+2}^{T} \sum_{j=1}^{q} \sum_{l=1}^{q} a_{T}(j)a_{T}(l) \left( E[\Sigma_{t=1}^{T} \int Z_{q,r}(v,v') dW dW']^{2} \right)^{1/2} \left( E[\Sigma_{t=1}^{T} Z_{q,r}(v,v')]^{2} \right)^{1/2} \leq O(qp^{4}/T).$$
Proof of Lemma A14. The result that $E[\sum_{t=2q+2} V_{3q}(t)]^2 = O(qp^2/T)$ by Minkowski's inequality and

$$E[V_{3q}(t)]^2 \leq \left[ \sum_{j=1}^{q} \sum_{t=1}^{q} a_T(j)a_T(l) \left| \int E[\epsilon_{q,T}^2 \psi_{q,-j}(v)\psi_{q,-l}(v')] \right|^2 \right]^{1/2} dW(v) dW(v')$$

$$\times \left[ \sum_{s=1}^{t-2q-1} E[\epsilon_q,s\psi_{q,s-j}(v)\psi_{q,s-l}(v')] \sum_{s=2q+2}^{t-2q-1} E[\epsilon_q,s\psi_{q,s-j}(v)\psi_{q,s-l}(v')] \right]^{1/2} dW(v) dW(v')$$

$$\leq 2Ctq \left[ \sum_{j=1}^{q} a_T(j) \right]^4 = O\left(\frac{qp^2}{T^4}\right). \quad \Box$$

Proof of Lemma A15. The result that $E[\sum_{t=2q+2} V_{4q}(t)]^2 = O(p)$ follows from Minkowski's inequality, $p \to \infty$, and the fact that

$$E[V_{4q}(t)]^2 = E \left[ \sum_{j=1}^{q} \sum_{t=1}^{q} a_T(j)a_T(l) \left| \int E[\epsilon_{q,T}^2 \psi_{q,-j}(v)\psi_{q,-l}(v')] \right|^2 \right]^{1/2} dW(v) dW(v')$$

$$\times \left[ \sum_{s=1}^{t-2q-1} E[\epsilon_q,s\psi_{q,s-j}(v)\psi_{q,s-l}(v')] \sum_{s=2q+2}^{t-2q-1} E[\epsilon_q,s\psi_{q,s-j}(v)\psi_{q,s-l}(v')] \right]^{1/2} dW(v) dW(v')$$

$$= \sum_{j=1}^{q} \sum_{t=1}^{q} a_T(j)a_T(l) \left| \int \prod_{j=2}^{q} E[\epsilon_{q,T}^2 \psi_{q,-j}(v)\psi_{q,-l}(v')] \right|^2 \prod_{j=2}^{q} dW(v) dW(v')$$

$$\times \left[ \sum_{s=1}^{t-2q-1} E[\epsilon_q,s\psi_{q,s-j}(v)\psi_{q,s-l}(v')] \sum_{s=2q+2}^{t-2q-1} E[\epsilon_q,s\psi_{q,s-j}(v)\psi_{q,s-l}(v')] \right]^{1/2} dW(v) dW(v')$$

$$\leq O\left(\frac{t^2p^2}{T^4}\right)$$

given Assumptions A2 and A8 (i.e. $\sum_{j=1}^{\infty} |\epsilon_j(u,v)| \leq C$ and $\sum_{j=1}^{\infty} \sum_{l=1}^{\infty} |E[(\epsilon_0^2 - \sigma^2)\psi_{-j}(u)\psi_{-l}(v)]| \leq C$). \quad \Box

Proof of Theorem 2. We consider $\hat{M}_1(p)$ only. The proof of Theorem 2 consists of the proofs of Theorems A4 and A5 below.

**Theorem A4.** Under the conditions of Theorem 2, $(p^{1/2}/T)[\hat{M}_1(p) - M_1(p)] \overset{P}{\to} 0.$

**Theorem A5.** Under the conditions of Theorem 2,

$$(p^{1/2}/T)[\hat{M}_1(p) - M_1(p)] \overset{P}{\to} (2D)^{-1/2} \pi \int f(0,1,0) (\omega, 0, v) - f(0,1,0) (\omega, 0, v))^2 d\omega dW(v).$$

**Proof of Theorem A4.** It suffices to show that

$$T^{-1} \sum_{j=1}^{T-1} \int k^2(j/p) T_j \left[ \hat{\sigma}_j^{(1,0)}(0, v)^2 - \tilde{\sigma}_j^{(1,0)}(0, v)^2 \right] dW(v) \overset{P}{\to} 0, \quad (A.33)$$

$$p^{-1} [\hat{C}_1(p) - \tilde{C}_1(p)] = O_P(1), \quad \text{and} \quad p^{-1} [\hat{D}_1(p) - \tilde{D}_1(p)] \overset{P}{\to} 0,$$

where $\hat{C}_1(p)$ and $\tilde{C}_1(p)$ are defined in the same way as $C_1(p)$ and $\tilde{C}_1(p)$ in (3.11), with $\{\epsilon_t\}_{t=1}^T$ replacing $\{\tilde{\epsilon}_t\}_{t=1}^T$. Since the proofs for $p^{-1} [\hat{C}_1(p) - \tilde{C}_1(p)] = O_P(1)$ and $p^{-1} [\hat{D}_1(p) - \tilde{D}_1(p)] \overset{P}{\to} 0$ are straightforward, we focus on the proof of (A.33). From (A.7), the Cauchy–Schwarz inequality, and the fact that $T^{-1} \int \sum_{j=1}^{T-1} k^2(j/p) T_j \left[ \hat{\sigma}_j^{(1,0)}(0, v)^2 - \tilde{\sigma}_j^{(1,0)}(0, v)^2 \right] dW(v) = O_P(1)$ as implied by Theorem A5 (the proof of Theorem A5 does not depend on Theorem A4, it suffices to show that $T^{-1} \hat{A}_1 \overset{P}{\to} 0$, where $\hat{A}_1$ is defined as in (A5)). Given (A6), we shall show that $T^{-1} \int \sum_{j=1}^{T-1} k^2(j/p) T_j \left[ \hat{\sigma}_j^{(1,0)}(0, v)^2 - \tilde{\sigma}_j^{(1,0)}(0, v)^2 \right] dW(v) \overset{P}{\to} 0, \quad a = 1, \ldots, 6$. We first consider $a = 1$. By the Cauchy–Schwarz inequality and $\hat{\delta}_l(v) \leq 2$, we have

$$|\hat{\sigma}_j^{(1,0)}(0, v)|^2 \leq T^{-1} \sum_{t=j+1}^{T} \left( \hat{\sigma}_l(v) - \tilde{\sigma}_l(v) \right)^2 \left( T^{-1} \sum_{t=j+1}^{T} \tilde{\sigma}_l(v)^2 \right) \leq T^{-1} \sum_{t=j+1}^{T} \left( \hat{\sigma}_l(v) - \tilde{\sigma}_l(v) \right)^2.$$


It follows from (A.3) and (A.7) and Assumption A7 that
\[ T^{-1} \int \sum_{j=1}^{T-1} k^2(j/p)T_j |(a_j - \hat{a}_j)|^2 dW(v) \leq \left[ \sum_{t=1}^{T} (\hat{\theta}_t - \theta_t)^2 \right] \sum_{j=1}^{T-1} a_T(j) \left[ \int dW(v) \right]^2 = O_P(p/T). \]

The proof for \( a = 2 \) is similar, noting that \( |T_j^{-1} \sum_{t=1}^{T} (\hat{\theta}_t - \theta_t)^2 | \leq T_j^{-1} \sum_{t=1}^{T} (\hat{\theta}_t - \theta_t)^2 |. \)

Next, we consider \( a = 3. \) By the Cauchy–Schwarz inequality, we have
\[ |\hat{a}_j - \hat{a}_j| \leq \left( T_j^{-1} \sum_{t=1}^{T} (\hat{\theta}_t - \theta_t)^2 \right) T_j^{-1} \sum_{t=1}^{T} (\hat{\theta}_t - \theta_t)^2. \]

It follows that
\[ T^{-1} \int \sum_{j=1}^{T-1} k^2(j/p)T_j |(a_j - \hat{a}_j)|^2 dW(v) \leq \left( T^{-1} \sum_{t=1}^{T} (\hat{\theta}_t - \theta_t)^2 \right) \sum_{j=1}^{T-1} k^2(j/p) \int v^2 dW(v) = O_P(p/T). \]

The proof for \( a = 4, 5, 6 \) is similar to that for \( a = 3. \) noting that \( |T_j^{-1} \sum_{t=1}^{T} (\hat{\theta}_t - \theta_t)^2 | \leq T_j^{-1} \sum_{t=1}^{T} (\hat{\theta}_t - \theta_t)^2 |. \) This completes the proof for Theorem A4.

**Proof of Theorem A5.** The proof is very similar to Hong (1999, Proof of Thm. 5), for the case \((m, l) = (1, 0)\) and \(W_1(\cdot) = \delta(\cdot), \) the Dirac delta function.

**Proof of Theorem 3.** Again, we only consider \( \hat{M}_1(p). \) We shall show Theorems A6 and A7 below.

**Theorem A6.** Under the conditions of Theorem 3, \( \hat{M}_1(p) - M_1(p) \overset{p}{\rightarrow} 0. \)

**Theorem A7.** Under the conditions of Theorem 3, \( M_1(p) - M_1(p) \overset{p}{\rightarrow} 0. \)

**Proof of Theorem A6.** Put \( \tilde{B} = \sum_{j=1}^{T-1} k^2(j/p)T_j \int |(a_j - \hat{a}_j)|^2 dW(v). \) It suffices to show \( p^{-\frac{1}{2}} \tilde{B} \overset{p}{\rightarrow} 0. \)

Given the conditions on \( k(\cdot), \) there exists a symmetric monotonic decreasing function \( k_0(z) \) in \( z > 0 \) such that \( k(z) \leq k_0(z) \) for all \( z > 0, \) and \( k_0(z) \) satisfies Assumption A6. It follows that for any constants \( \epsilon, \eta > 0, \)
\[ P(p^{-\frac{1}{2}} \tilde{B} > \epsilon) \leq P(p^{-\frac{1}{2}} \tilde{B} > \epsilon, |\hat{p}/p - 1| \leq \eta) + P(|\hat{p}/p - 1| > \eta). \]
where the second term vanishes for all \( \eta > 0, \) asymptotically given \( \hat{p}/p - 1 \overset{p}{\rightarrow} 0. \) Thus it remains to show that the first term also vanishes as \( T \rightarrow \infty. \)

Because \( \hat{p}/p - 1 \leq \eta \) implies \( \hat{p} \leq (1 + \eta)p, \) we have that for \( |\hat{p}/p - 1| \leq \eta, \)
\[ p^{-\frac{1}{2}} \tilde{B} \leq (1 + \eta)^{\frac{1}{2}} (1 + \eta)p^{-\frac{1}{2}} \sum_{j=1}^{T-1} k^2(j/(1 + \eta)p)T_j |(a_j - \hat{a}_j)|^2 dW(v) = 0 \]
for any \( \eta > 0 \) given (A.6), where the inequality follows from the fact that \( |k(z)| \leq |k_0(z)| \) This completes the proof of Theorem A6.

**Proof of Theorem A7.** Put \( Q(p) = 2\pi \sum_{j=1}^{T-1} k^2(j/p)T_j \int |(a_j - \hat{a}_j)|^2 dW(v). \) Then we can write
\[
M_1(p) - M_1(p) = \left[ \hat{Q}(p) - \hat{C}_1(p) \right] \sqrt{\hat{D}(p)} - \left[ Q(p) - \hat{C}_1(p) \right] \sqrt{\hat{D}(p)}
\]
\[ = \left[ \hat{Q}(p) - Q(p) - \hat{C}_1(p) - \hat{C}_1(p) \right] \sqrt{\hat{D}(p)} + M_1(p) \left[ \sqrt{\hat{D}(p)} \hat{D}(p) - 1 \right]. \]

Following a reasoning analogous to the proof of Hong (1999, Thm. 4), we can obtain \( p^{-\frac{1}{2}} [\hat{Q}(p) - Q(p)] \overset{p}{\rightarrow} 0 \) under \( H_0. \) This and Lemma A16 below imply \( M_1(p) - M_1(p) \overset{p}{\rightarrow} 0. \) Hence, \( M_1(p) \overset{d}{\rightarrow} N(0, 1). \)
Lemma A16. Suppose Assumptions A6 and A8 hold. If \( \hat{p} / p = 1 + O(p^{-1}) \) for some \( \beta > 1 + \frac{1}{4h_2} \), where \( h \) is as in Assumption A6 and \( p = cn^k \) for \( 0 < h < (3 + \frac{1}{4h_2})^{-1} \) and \( 0 < c < \infty \). Then \[ p^{-1/2} \left[ \hat{C}_1(p) - \hat{C}_1(p) \right] \overset{p}{\to} 0 \] and \( p^{-1} [ D(p) - D(p) ] \overset{p}{\to} 0 \).

Proof of Lemma A16. The proof is analogous to the proof of Lemma A.2 in Hong (1999, pp. 1217–1218). Note that the factors \( \sum_{j=1+k} T \hat{C}_j(p) \) and \( \sum_{j=1} T \hat{C}_j(p) \) in Lemma A.2 of Hong (1999), but this does not alter the proof much, provided that we apply Markov’s inequality to obtain the orders of magnitude for the terms involving these stochastic factors. Note also that the condition \( \lambda \in (0, 1) \) as imposed in Hong (1999) is implied by the condition that \( 0 < h < (3 + \frac{1}{4h_2})^{-1} \).

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