Fundamental Asymmetries in US Monetary Policymaking: Evidence from a Nonlinear Autoregressive Distributed Lag Quantile Regression Model*

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Abstract

We identify three general forms of asymmetry that may characterise a wide range of economic processes: reaction asymmetry, adjustment asymmetry and locational asymmetry. The first relates to the possibility that the long-run response of one variable to another may be regime sensitive. The second refers to the case in which the pattern of dynamic adjustment to long-run equilibrium may be state-contingent. The third relates to the notion that an economic relationship may depend upon which conditional quantile of the dependent variable a given observation belongs. Based on a synthesis of the nonlinear ARDL (Autoregressive Distributed Lag) model developed by Shin, Yu and Greenwood-Nimmo (2009) and the quantile regression approach of Koenker and Bassett (1978), we develop a new empirical framework capable of coherently and simultaneously modelling these three asymmetries. The application of this model to US monetary policymaking over the period 1964q2-2008q2 reveals the following phenomena: (i) The Fed responds linearly to both output and inflation, and does not adhere to the Taylor principle in the lower quantiles of the interest rate, mainly due to the proximity of the zero lower nominal bound; (ii) Between the fortieth and eightieth quantiles, the Taylor principle is upheld for positive inflationary shocks only. Meanwhile, we note significant responses to both positive and negative output gap shocks, with a marked negative asymmetry, suggesting that the Fed acts as an inflation hawk while also displaying a marked tendency toward growth-fostering policies; (iii) Finally, for the uppermost quantiles, we find evidence of very aggressive policy responses to positive and negative inflation.

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and output gap shocks in the context of profound response asymmetry. Hence, we conclude that the degree of policy aggression is a monotonically increasing function of the conditional quantile of the interest rate, and that the common practice of confining one’s attention to the conditional mean of the dependent variable may obscure important underlying asymmetric effects.

**Keywords:** Nonlinear ARDL Model, Quantile Regression, Dynamic Multipliers, Reaction Adjustment and Locational Asymmetries, Asymmetric Central Bank Preferences.

**JEL Classifications:** C22, C51, E58.
1 Introduction

The analysis of non-linearities in the reaction function of the central bank is a young but vibrant science. We identify three general forms of asymmetry that may characterise monetary policy: reaction asymmetry, adjustment asymmetry and locational asymmetry. The first relates to differential interest rate long-run responses that may be elicited by heterogeneously positive or negative shocks to a given variable. The second describes the differential speed of interest rate to its equilibrium under various regimes. The third is associated with the notion that the reaction of the central bank to the inflation and output gaps may depend on the current location of the interest rate within its conditional distribution.

Our goal in this paper is to develop a general framework for asymmetric modelling that nests each of these three forms of nonlinearity as a special case. Essentially, this involves combining established approaches to short-run asymmetric modelling and long-run asymmetric modelling with the quantile regression approach popularised by Koenker and Bassett (1978). However, even ignoring the quantile extension, combining regime-switching short- and long-run models is likely to be non-trivial when the transition function is not common to both the short- and long-run (Saikkonen, 2008). We approach this issue pragmatically following the asymmetric ARDL approach originated by Shin, Yu and Greenwood-Nimmo (2009, hereafter SYG) which combines adjustment asymmetry with reaction asymmetry subject to a common transition function (in this case we impose a common known threshold value of zero in the construction of partial sum processes). One of the principal benefits of this approach is that, quite unlike the popular Markov-switching or smooth transition models, it is easily estimable by standard OLS. This simplicity renders it an ideal candidate for extension to the quantile case.

We apply both the standard nonlinear ARDL model estimated at the conditional mean of the interest rate distribution (the NARDL-M model) and its quantile extension (the NARDL-Q model) to the analysis of US monetary policy between 1964q2 and 2008q2. In the NARDL-M framework, we are unable to reject the null hypothesis of long-run reaction symmetry with respect to both inflation and output gaps. Furthermore, the null hypothesis of short-run symmetric adjustment cannot be rejected in relation to the output gap. This would typically lead us to conclude that the Federal Reserve has acted in a linear fashion in the long-run during this time but that its interest rate response to inflationary shocks has been more rapid than in the case of disinflationary shocks. However, the NARDL-Q specification estimated on a range of quantiles reveals pronounced locational asymmetry at higher levels of the interest rate. Our results indicate that the Fed has reacted very cautiously and in a linear fashion when the interest rate is low but that its policy response to both inflation and output gaps has been considerably more aggressive and markedly asymmetric when the interest rate is at higher levels. Hence, we conclude that the failure to account for locational asymmetry may mask other forms of asymmetry.

The paper proceeds in 5 sections. Section 2 reviews the existing literature on asymmetric central bank preferences, asymmetric policy adjustments and locational asymmetries in monetary policymaking. Section 3 introduces the asymmetric ARDL model and its quantile extension and offers a brief discussion of the different forms of asymmetry that can be modelled in this way. Section 4 presents the results of both the standard NARDL-M and NARDL-Q models of the reaction function of the Federal Reserve between 1964q2 and 2008q2. Section 5 concludes.

2 Asymmetric Monetary Policy

The ubiquitous Taylor (1993) rule models the central bank interest rate decision as a linear function of inflation relative to target (the inflation gap) and output relative to potential (the output gap). Underlying this framework is the assumption that the policymaker strives to minimise a
quadratic loss function in the inflation and output gaps. Recently, however, a growing body of literature has promoted the notion that the policy rule may be non-linear and the loss function non-quadratic (Blinder, 1997; Granger and Pesaran, 2000; Cukierman and Muscatelli, 2008). Chief among the reasons for this non-linearity are the notion that correcting a negative output gap may be more difficult than closing a positive output gap (the ‘pushing on a string’ argument) and the possibility that inflation may have a tendency to rise more easily than it falls (the rationale for inflation-hawkism).

Nobay and Peel (2003) demonstrate that the optimal policy solution in a theoretical framework in which policymakers preferences are modelled asymmetrically involves both an inflation target and a linear Walsh (1995) contract. They conclude that asymmetric modelling adds realism to the analysis of monetary policy and that it may yield results distinctly inconsistent with the case of quadratic preferences. Furthermore, Siklos and Wohar (2005) extend the authors’ work and argue that the careful construction of asymmetric error-correction models can potentially overcome the problems associated with breaks in the structure of the underlying data. The motivation for the development of asymmetric models is apparent.

An early and notable contribution to the empirical literature was made by Ruge-Murcia (2003). Based on a simple game-theoretic framework in which positive and negative inflationary gaps can be weighted differently by policymakers, the author finds that estimated asymmetric reactions functions for Canada, Sweden and the UK yield results that are quantitatively distinct from those of a symmetric specification. He concludes that asymmetric preferences may explain the negative mean of the inflation gap in these three countries.

Dolado, Maria-Dolores and Naveira (2005) employ a novel approach in which the loss function of the central bank remains quadratic but the specification of the Phillips curve is nonlinear. They demonstrate that this framework also generates nonlinearity in the reaction function of the central bank. Using the Euler equation approach associated with Clarida, Galí and Gertler (1998) as well as the ordered probit approach suggested by Dolado and Mari-Dolores (2002), the authors find substantial evidence of nonlinearities in Germany, France and Spain but not in the USA. In particular, their results indicate that European central banks have systematically responded more strongly to positive than negative inflation and output gaps. They attribute this finding to labour market rigidities present only in the European countries.

Asymmetric preferences have been widely modelled as threshold effects. Bec, Salem and Collard (2000) use the lagged output gap to determine threshold transitions in a STAR framework and find that the interest rate response to inflation is stronger in a recessionary environment than a boom environment. Martin and Milas (2004) assume that regime transitions are governed by a quadratic logistic function in expected inflation. Using this approach, they find that the Bank of England has pursued an asymmetric policy in which positive inflation gaps attract a more aggressive response than negative gaps. Moreover, their results indicate that the Bank adopted a de facto target band of 1.4% - 2.6% between 1992 and 2000. Bunzel and Enders (2005) estimate a simple threshold model and find that the Greenspan Fed did not responded to inflation below a threshold of approximately 2.3% but that an inertial Taylor-type rule has characterised its behaviour at higher rates of inflation. Similarly, Petersen (2007) finds that the Fed followed a nonlinear Taylor rule under both Volcker and Greenspan but that monetary policy was linear in the pre-Volcker era. More specifically, he finds that, since 1985, the Fed has reacted more aggressively to inflation when it is at higher levels than when the price-level is growing slowly, with the transition from low to high inflation occurring between 3.3% and 3.8% in his smooth-transition framework. This leads him to conclude that nonlinearity is associated with enlightened policymaking.

1By contrast, Surico (2007) identifies non-linearity with respect to the output gap in the pre-Volcker period only, and concludes that this form of asymmetry generated an average positive inflationary bias of 1.5% in the
A voluminous literature has grown around the notion of temporal change in the policy reaction function, perhaps driven by changes in the mandate of the central bank or in the nature of the macroeconomy. A recent example is provided by Raggi, Greco and Castelnuovo (2008), in which the authors estimate a Taylor rule with time-varying trend inflation where transitions between active and passive monetary policy regimes are governed by an unobserved underlying Markov chain. In order to estimate their model, the authors employ the popular Gibbs sampler in a Bayesian MCMC approach. Their results strongly suggest that the inflation target in the USA has been time-varying. Moreover, their state probabilities indicate, to a first approximation, that US monetary policy was passive between 1968 and 1975 and 1980-85 but that a modified Taylor principle was upheld elsewhere.

Subject to the feasibility of an appropriate mapping between the time index and the covariates of the reaction function, such intertemporal regime-switching models can be related approximately to the asymmetric models discussed above. The general consensus to emerge from the regime-switching literature is that US monetary policy became increasingly anti-inflationary in the Volcker-Greenspan era\(^2\). Moreover, a crude generalisation of the historical experience of US monetary policy may be that the Burns-Miller period was one of high inflation and a volatile output gap, the Greenspan-Bernanke era has been one of low inflation and greater economic stability (until recently at least) and the Volcker years account for the transition. Hence, it seems likely that results similar to those adduced by Raggi et al. could be achieved by a model in which state transitions are determined according to the behaviour of these core macroeconomic variables.

The papers surveyed above have dealt variously with what were termed reaction (long-run) and adjustment (short-run) asymmetries in the opening paragraph of this paper. However, it is possible that the response of the central bank to the inflation and output gaps may also depend upon the level of the interest rate itself. This natural means by which to investigate such locational asymmetry is by use of the quantile regression approach associated originally with Koenker and Bassett (1978) and subsequently with Koenker and Hallock (2001) and Koenker and Xiao (2006).

Symmetric quantile regression models have been widely used in a number of fields, notably the analysis of stock market returns (e.g. Barnes and Hughes, 2002) and in labour economics (e.g. Falaris, 2004; Martins and Pereira, 2004). However, at the time of writing, we are aware of only two papers that have applied quantile techniques to the analysis of monetary policy. Mizen, Kim and Thanaset (2009, hereafter MKT) consider the case of locational asymmetry at the Fed and the Bank of Japan in the context of an otherwise symmetrical forward-looking monetary policy rule. Their results indicate that the Taylor principle is upheld at every conditional quantile and that degree of policy aggression measured by the magnitude of the coefficient on inflation is a monotonically increasing function of the conditional quantile of the interest rate.

More recently, Wolters (2009) has applied the quantile regression framework to the analysis of US monetary policy. His results suggest that the policy response to inflation increases over the conditional distribution of the Federal funds rate, while the reaction to output gap disequilibria decreases. In conjunction with the results of MKT, these results clearly indicate that the widespread convention of modelling the policy rule at the conditional mean of the interest rate distribution may provide misleading results. However, neither Wolters nor MKT are able to convincingly address issues relating to reaction or adjustment asymmetries in their empirical monetary policy of the time.

\(^2\)This consensus is not, however, absolute. Recently, Cukierman and Muscatelli (2008) have found that it was not inflation-avoidance but recession-avoidance that characterised the Greenspan years. Similarly, employing a novel approach to combining persistent and stationary series in a vector error correction model, Greenwood-Nimmo and Shin (2009) find that US monetary policy has been distinctly growth-oriented since the end of Volcker’s tenure and that there is little evidence that the Taylor principle has been observed post-Volcker. A similar conclusion is reached by Petersen (op. cit.), who concludes that the Taylor principle is not required for effective monetary policy if the reaction function is non-linear.
frameworks. The development of a synthetic approach to the analysis of these three forms of nonlinearity is the focus of this paper. We will propose a simple means of combining the asymmetric ARDL approach originated by SYG with the quantile regression model, thereby achieving a tractable framework capable of modelling fundamentally asymmetric processes in a coherent and intuitively appealing manner.

3 The Asymmetric ARDL Model

Shin, Yu and Greenwood-Nimmo (2009) advance a simple technique for modelling both long- and short-run asymmetries in a coherent manner. The model is essentially an asymmetric extension of the linear ARDL approach to modelling long-run (cointegrating) levels relationships originated by Pesaran and Shin (1998) and Pesaran, Shin and Smith (2001, PSS). Consider the asymmetric cointegrating relationship:

\[ y_t = \beta^+ x_t^+ + \beta^- x_t^- + u_t, \]

where \( x_t \) is a \( k \times 1 \) vector of regressors decomposed as:

\[ x_t = x_0 + x_t^+ + x_t^-, \]

where \( x_t^+ \) and \( x_t^- \) are partial sum processes of positive and negative changes in \( x_t \) defined by:

\[ x_t^+ = \sum_{j=1}^{t} \Delta x_j^+ = \sum_{j=1}^{t} \max(\Delta x_j, 0), \quad x_t^- = \sum_{j=1}^{t} \Delta x_j^- = \sum_{j=1}^{t} \min(\Delta x_j, 0), \]

and \( \beta^+ \) and \( \beta^- \) are the associated asymmetric long-run parameters. The extension of (3.1) to the ARDL\((p,q)\) case is straightforward, yielding the following asymmetric error correction model:

\[ \Delta y_t = \rho y_{t-1} + \theta^+ x_{t-1}^+ + \theta^- x_{t-1}^- + \sum_{j=1}^{p-1} \varphi_j \Delta y_{t-j} + \sum_{j=0}^{q} \left( \pi_j^+ \Delta x_{t-j}^+ + \pi_j^- \Delta x_{t-j}^- \right) + \varepsilon_t. \]
\[
\Delta y_t = \rho y_{t-1} + \theta x_{t-1} + \sum_{j=1}^{p-1} \varphi_j \Delta y_{t-j} + \sum_{j=0}^{q} \pi_j \Delta x_{t-j} + \varepsilon_t. \tag{3.5}
\]

Finally, the asymmetric ARDL model, (3.4) can be used to derive the asymmetric cumulative dynamic multiplier effects of a unit change in \(x_t^+\) and \(x_t^-\) respectively on \(y_t\), defined by:

\[
\begin{align*}
\mathbf{m}_h^+ &= \sum_{j=0}^{h} \frac{\partial y_{t+j}}{\partial x_t^+}, & \mathbf{m}_h^- &= \sum_{j=0}^{h} \frac{\partial y_{t+j}}{\partial x_t^-}, & h &= 0, 1, 2...
\end{align*}
\tag{3.6}
\]

Notice that, by construction, as \(h \to \infty\), \(\mathbf{m}_h^+\) and \(\mathbf{m}_h^-\) tend to approach the respective asymmetric long-run coefficients. At present, we evaluate the differential effects of positive and negative shocks to the explanatory variables under the assumption of a single known threshold value. Indeed, the construction of positive and negative partial sum processes relies on the imposition of a zero threshold. However, this assumption can be easily relaxed to accommodate the more general case of multiple unknown threshold decompositions (Greenwood-Nimmo, Shin and Van Treeck, 2009). Similarly, we currently work under the implicit assumption that positive and negative shocks to the explanatory variables occur with equal probability. In the current context this is a largely innocuous simplification as the mean values of \(\Delta \pi\) and \(\Delta y\) are relatively close to zero over our sample, implying that \(\Pr(\Delta x > 0) \approx \Pr(\Delta x < 0) \approx 0.5\). However, in the general case in which this condition is not satisfied, as with all regime-switching models, one must allow for the impact of the respective regime probabilities in the evaluation of the asymmetric dynamic multipliers.

The ability of the dynamic multipliers to illuminate the traverse between initial equilibrium, short-run disequilibrium following a shock, and a new long-run equilibrium makes them a powerful tool for the combined analysis of (short-run) adjustment asymmetry and (long-run) response asymmetry. This property is likely to prove particularly advantageous in the analysis of asymmetric central bank preferences.

### 3.1 The Quantile Extension of the NARDL Model

As MKT note, conventional regression techniques such as OLS, IV, or GMM evaluate the relationship between series at the mean of the conditional distribution of the dependent variable (p. 4). The implicit assumption is that the estimated relationship holds not only at the mean, but also in other parts of the conditional distribution of the dependent variable. In many cases, there is little reason to believe that this is an innocuous assumption. The relationship between the dependent variable and its covariates may differ depending on the location of the dependent variable over its own conditional distribution.

The quantile regression model corresponding to the NARDL-M model in (3.4) is given by

\[
\begin{align*}
\Delta y_t &= \rho(\kappa)y_{t-1} + \theta^+(\kappa)x_{t-1} + \theta^-(\kappa)x_{t-1} + \sum_{j=1}^{p-1} \varphi(\kappa,j) \Delta y_{t-j} + \sum_{j=0}^{q} \left( \pi^+(\kappa,j) \Delta x_{t-j}^+ + \pi^-(\kappa,j) \Delta x_{t-j}^- \right) + \varepsilon(\kappa)_t \\
&= z_t' \alpha(\kappa) + \varepsilon(\kappa)_t,
\end{align*}
\]

where \(\kappa\) is a given quantile index in \((0, 1)\), \(z_t\) is the vector of all regressors in the quantile model and \(\alpha(\kappa)\) is the vector obtained by collecting all the coefficients in the model. We impose the usual assumption that the conditional quantile model is correctly specified; that is,

\[E(\psi(\varepsilon(\kappa)_t)|z_t) = 0\]
where \( \psi_\kappa(z) = \kappa - 1[z \leq 0] \). This assumption is equivalent to the following:

\[
\int_{-\infty}^{\psi_\kappa(z)} f_{\Delta y_t|z_t}(t|z_t) dt = \kappa
\]

with the conditional density of \( f_{\Delta y_t|z_t}(t|z_t) \) is the density of \( \Delta y_t \) conditional on \( z_t \). Hence, it can be easily seen that the assumption implies that \( z_t^\kappa \alpha(\kappa) \) is the correct conditional quantile of \( \Delta y_t \) given \( z_t \) when the quantile index is given by \( \kappa \in (0, 1) \). Our objective is to analyse how \( z_t \) affects \( \Delta y_t \) over the range of the conditional distribution. This can achieved by estimating the conditional quantile for various values of \( \kappa \) over \((0, 1)\).

By admitting non-linearity of the form modelled by (3.4) into the conditional quantile function, we obtain the quantile-NARDL or NARDL-Q model. For a fixed value of \( \kappa \), the single-step quantile regression estimates of the model parameters are those values that minimise the following expression:

\[
\min_{\alpha(\kappa)} \sum_{t=1}^{T} \xi_{(\kappa)} \{ \Delta y_t - z_t^\kappa \alpha(\kappa) \}
\]

where \( \xi_{(\kappa)}(z) \) is the usual check function defined as \( \xi_{(\kappa)}(z) = z(\kappa - 1[z \leq 0]) \) (c.f. Koenker and Hallock, 2001). The solution from this minimization denoted by \( \hat{\alpha}(\kappa) \) will be consistent and asymptotically normal under the correct quantile specification assumption with a few more regularity conditions. Finally, the dynamic multipliers associated with the \( \kappa \)th conditional quantile of the dependent variable may be written as:

\[
\begin{align*}
    m^+_{(\kappa)h} &= \sum_{j=0}^{h} \frac{\partial y_{(\kappa)t+j}}{\partial x_t^+}, \\
    m^-_{(\kappa)h} &= \sum_{j=0}^{h} \frac{\partial y_{(\kappa)t+j}}{\partial x_t^-}, \\
    h &= 0, 1, 2, ...
\end{align*}
\]

Kim and Muller (2005, 2010) demonstrate that the single-step quantile estimation routine outlined above is biased when there exists non-zero contemporaneous correlation between the explanatory variables and the residuals. This is likely to be particularly problematic for forward-looking models incorporating expectational terms, such as that developed by MKT. In this case, either the two-stage estimation procedure advanced by Kim and Muller or the inverse quantile regression technique of Chernozhukov and Hansen (2005) could be used to achieve reliable estimation. While we do not consider forward-looking modelling and the ARDL model is known to correct perfectly for the endogeneity of \( I(1) \) regressors (Pesaran and Shin, 1998), any contemporaneous correlation between the stationary output gap series and the regression residuals could be problematic.

The NARDL-Q framework is able to explicitly model the following three types of asymmetry:

(i.) **Reaction asymmetry** - captured by the heterogeneous long-run parameters \( \beta^+_{(\kappa)} \) and \( \beta^-_{(\kappa)} \), this reflects the different long-run responses of the dependent variable to positive and negative changes in the explanatory variables.

(ii.) **Adjustment asymmetry** - captured by the differences between the estimated short-run parameters, \( \pi^+_{(\kappa)j} \) and \( \pi^-_{(\kappa)j} \) for \( j = 0, ..., q \), this represents the differential impact effects of \( x^+ \) and \( x^- \) on \( y \) and the associated dynamic adjustment toward the respective long-run multipliers.

(iii.) **Locational asymmetry** - captured by the differences between the short- and long-run parameters estimated at various quantiles of the dependent variable, this relates to the changing response of the dependent variable to the explanatory variables at different values of \( \kappa \).
In order to statistically discriminate between the various forms of asymmetry, we propose the following array of hypothesis tests:

(i.) \( H_0: \beta^+_{(\kappa)} = \beta^-_{(\kappa)} \) vs. \( H_1: \beta^+_{(\kappa)} \neq \beta^-_{(\kappa)} \).

(ii-a.) \( H_0: \pi^+_{(\kappa)j} = \pi^-_{(\kappa)j} \) vs. \( H_1: \pi^+_{(\kappa)j} \neq \pi^-_{(\kappa)j} \) for \( j = 0, \ldots, q \).

(ii-b.) \( H_0: \sum_j \pi^+_{(\kappa)j} = \sum_j \pi^-_{(\kappa)j} \) vs. \( H_1: \sum_j \pi^+_{(\kappa)j} \neq \sum_j \pi^-_{(\kappa)j} \) for \( j = 0, \ldots, q \).

It follows from SYG that the Wald statistics testing the null hypothesis of reaction symmetry and of pairwise and additive adjustment symmetry in the \( \kappa \)th conditional quantile will follow an asymptotic \( \chi^2 \) distribution, respectively.

Further, we consider the following hypotheses:

(iii.) \( H_0: \beta^+_{(h)} = \beta^-_{(h)}; \beta^+_{(k)} = \beta^-_{(k)} \) vs. \( H_1: \beta^+_{(h)} \neq \beta^-_{(h)}; \beta^+_{(k)} \neq \beta^-_{(k)} \) for \( h, k = \{0.1, \ldots, 0.9\}, h \neq k \).

The test for long-run locational symmetry follows an asymptotic \( \chi^2 \) distribution.

(iv.) \( H_0: \pi^+_{(h)j} = \pi^-_{(h)j}; \pi^+_{(k)j} = \pi^-_{(k)j} \) vs. \( H_1: \pi^+_{(h)j} \neq \pi^-_{(h)j}; \theta^+_{(h)} \neq \theta^-_{(k)} \) for \( h, k = \{0.1, \ldots, 0.9\}, h \neq k, j = 1, \ldots, q \). The test for short-run locational symmetry follows an asymptotic \( \chi^2 \) distribution.

While (i), (ii-a), (ii-b) focus on a given quantile index \( \kappa \), (iii) and (iv) consider a range of quantile indices and test for a change or consistency of any model characteristics over the range. For example, one can investigate the issue of whether there exists the same short-run reaction asymmetry in the lower part (e.g. 10%) as well as in the upper tail (e.g. 90%) of the conditional distribution, which can be expressed as

\[
H_0: \pi^+_{(0.1)} = \pi^-_{(0.1)} \text{ and } \pi^+_{(0.9)} = \pi^-_{(0.9)}.
\]

For this test, it is necessary to estimate multiple quantiles simultaneously and the asymptotic normality of multiple quantiles have been derived in the literature, e.g. Koenker and Bassett (1978). For the above example, it can be shown that with \( \kappa_i = 0.1 \) and \( \kappa_j = 0.9 \),

\[
T^{1/2} \left( \hat{\pi}^+_{(\kappa_i)} - \pi^+_{(\kappa_i)} \right) \Rightarrow N(0_{2 \times 1}, \Omega \otimes Q)
\]

where

\[
\Omega = [\omega_{ij}], \quad \omega_{ij} = \frac{\kappa_i(1 - \kappa_j)}{f(F^{-1}(\kappa_i))f(F^{-1}(\kappa_j))}
\]

Hence, the Wald statistics testing the null hypothesis of location symmetry between the \( \kappa_i \) and \( \kappa_j \)th conditional quantiles will follow an asymptotic \( \chi^2 \) distribution. See Kim and Shin (2010) for further details.

4 Estimation Results

We estimate the asymmetric Taylor rule for the US between 1964q2 and 2008q2 using both the standard asymmetric ARDL framework derived by SYG (henceforth the NARDL-M model) and the NARDL-Q model described above. The NARDL-M model evaluates the relationship

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4 All data were retrieved from the IMF’s International Financial Statistics. Potential output was calculated using the Hodrick-Prescott filter with the smoothing parameter selected by the Ravn-Uhlig (2002) frequency rule.
between the variates at the conditional mean of the interest rate, as has become common practice in the empirical literature. By contrast, using the NARDL-Q model, we obtain estimates of the relationship at a range of quantiles across the entire conditional distribution. In this way we can investigate the response of the Federal Reserve to inflation and output at various levels of the interest rate, thereby shedding light on potential locational asymmetries and the nature of policymaking in the neighborhood of the zero nominal lower bound.

4.1 The NARDL-M Model

Table 1 presents the results of NARDL-M estimation of the asymmetric Taylor rule where $i_t$ denotes the short-term nominal interest rate, $\pi_t$ the rate of consumer price inflation, and $y_t$ the output gap. The four columns of the table relate to the four general combinations of short- and long-run asymmetry identified by SYG. The PSS F-test identifies the existence of a long-run levels relationship at the 5% level in all cases. However, the long-run symmetry restrictions with respect to both inflation and the output gap cannot be rejected at the 5% confidence level regardless of the specification of the model dynamics. Furthermore, we find only weak support for additive adjustment asymmetry with respect to either inflationary shocks or output gap shocks. It is clear, however, that we observe pairwise asymmetric adjustment in columns 1 and 3 where short-run symmetry restrictions are not imposed during estimation.

| TABLE 1 ABOUT HERE |

Figures 1 and 2 plot the cumulative dynamic multipliers associated with unit shocks to inflation and the output gap, respectively (or the associated positive and negative partial sum processes). The dynamic response of the interest rate to the output gap is qualitatively similar under all specifications, suggesting that the response of the Federal Reserve to output gap disequilibrium is indeed linear at the conditional mean of the interest rate. By contrast, the dynamic multipliers obtained under the assumption of long-run symmetric responses to inflation gaps are quite different from those derived from the asymmetric case which indicates that the Fed has responded more aggressively to positive than to negative inflation gaps. The inability of the Wald test to reject the long-run symmetry restrictions in this case results from the presence of a non-negligible negative covariance. Hence, we are obliged to conclude that the NARDL-M model finds little evidence of asymmetry in the reaction function of the central bank. However, it remains to be seen whether this result may be safely generalised to the entire distribution of the interest rate.

| FIGURES 1 & 2 ABOUT HERE |

4.2 The NARDL-Q Model

We estimate the NARDL-Q model for $\kappa = \{0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90\}$ under the assumption of joint long- and short-run asymmetry where the lag structure is selected based on that presented in Table 1. Figures 3 - 5 plot the asymmetric cumulative dynamic multipliers with respect to inflation and output gap shocks at each conditional quantile of the interest rate. A general trend toward increasingly aggressive monetary policy as $\kappa$ increases is evident in the figures.

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5In all cases, general-to-specific lag selection was performed starting from an maximum lag length of 4 using a sequential 5% rule as implemented by Gretl version 1.8.2cvs.

6Note that the consideration of a broader range of models representing other feasible combinations of reaction and adjustment asymmetry on a variable-by-variable basis still provided little evidence of reaction asymmetry. The results of this analysis are available upon request.
The finding that monetary policy has responded more robustly to inflation and the output gap when the interest rate is higher is comparable with the findings of MKT. However, in their paper, the authors find that the Fed’s policy aggression, measured by the magnitude of the inflation and output gap coefficients, is monotone increasing in $\kappa$. Our results reveal a more complex relationship between the $\kappa$ and the coefficients of the reaction function. We find little difference between the reaction functions associated with $0.05 \leq \kappa \leq 0.4$. In this region, our results provide little support for the operation of the Taylor principle in the USA and relatively little evidence of reaction or adjustment asymmetries in relation to either inflation or the output gap. For $0.4 \leq \kappa \leq 0.7$, we observe a strong policy response to both positive and negative movements of the output gap and to positive inflationary pressures, with the Taylor principle upheld. By contrast, over this range of the interest rate, we note no significant response to disinflationary pressure over any horizon. Within this region, we find clear evidence of pronounced reaction asymmetry, suggesting that the Fed has systematically responded more strongly to positive than negative inflation gaps, and to negative than positive output gaps. Finally, for $0.8 \leq \kappa \leq 0.95$, our results indicate very strong responses to both positive and negative inflation and output gaps and very pronounced asymmetry acting in the same direction as before.

Our conjectures based on these results are twofold. Firstly, it appears that US monetary policymakers act on the basis that economic agents do not respond to the absolute magnitude of a policy innovation but to its size in relation to the current level of the interest rate. Hence, while a 25 basis point rate cut may be considered substantial when the interest rate is initially at just 2%, the same intervention would be considered mild when the starting value of the interest rate is 10%. This is an intuitively reasonable finding when one considers the effect of the rate change on the nominal cost-of-capital. In layman’s terms, the former is equivalent to a $1/8$ reduction in the cost-of-capital while the latter represents a reduction of just $1/40$. When viewed in this way, it is unsurprising that a larger interest rate change is required to achieve a given objective at higher levels of the interest rate.

Secondly, the observation that policy is conducted in a symmetrical fashion at low values of $\kappa$ but asymmetrically at higher values suggests that policymakers become increasingly hawkish toward inflation and dovish toward the output gap at higher conditional quantiles of the interest rate. It is tempting at first to dismiss this finding as an artefact of our sample given that the higher quantiles of the interest rate mostly relate to the Volcker Fed, which was known for its tough stance on inflation. The observed pattern of output gap asymmetry in relation to $\kappa$ can be explained by the notion that cash flow constraints are more likely to be binding in the presence of high inflation rates and hence high nominal interest rates (Greenwald and Stiglitz, 2003, pp. 38-9). Although the firm’s investment is equally profitable in real terms, it faces a potential cash flow constraint as long as the lender is not committed to lend the difference between the return from the investment and the nominal interest obligations. Hence, borrowing even at the same real interest rates becomes less attractive at high rates of inflation. The degree of uncertainty about future borrowing opportunities will be typically higher as the economy goes into a slump in which situation the Fed is likely to react more strongly to negative output gap changes at high nominal interest rates.

In the interests of clarity, we will now provide detailed results for the lower 10%, median, and upper 10% conditional quantiles. Table 2 summarises the parameter estimates at the three

---

7Suppose that a firm borrows $1,000 to buy an asset worth $2,000. Assume that the real interest rate and the rate of return are 5 and 10 per cent, respectively. With zero inflation, the nominal interest rate will be 5 per cent. After one year, the firm has to pay $50 in interests, which can be easily covered with the cash flow earned from the asset ($200). Now, suppose that inflation increases to 20 per cent and hence the nominal interest rate is 25 per cent. Then, the same cash flow of $200 is not enough to pay $250 owed in interests.
selected quantiles. Note that the pattern of significance does not change substantially between the quantiles, suggesting that our imposition of the lag structure derived from the NARDL-M model is generally appropriate.

TABLE 2 ABOUT HERE

Figure 6 plots the cumulative dynamic multipliers derived from the NARDL-Q model at the three selected quantiles. The patterns of dynamic adjustment to long-run equilibrium are quite striking and reveal the same pattern described by the three dimensional figures, but more clearly. The results show that monetary policy has been strictly symmetrical at the lower 10% quantile, with at most very mild adjustment asymmetry confined to the very short-run. By contrast, at the median, there is pronounced long-run asymmetry in relation to both inflation and output gap disequilibrium. The results indicate that the Taylor principle is satisfied in the case of positive inflationary pressure after a lag of approximately 10 quarters, reflecting inertial policymaking. By contrast, the interest rate response to disinflationary pressure is well below unity up to 40 quarters and barely approaches unity in the long-run. This is an interesting finding as it suggests that policymakers act as inflation hawks when the interest rate is within a ‘normal’ range, reacting more aggressively to rising inflation than to falling inflation. This reflects the common argument that, in normal times, inflation has a tendency to rise more readily than it falls (Bunzel and Enders, 2005). Similarly, we find that policymakers respond more strongly to negative than positive output gaps in this range, reflecting the accepted wisdom that it takes a substantial rate cut to close a negative output gap but only a relative small rate rise to eliminate a positive gap. In this sense, it is often argued that attempting to correct a negative gap using monetary policy is akin to pushing on a string. Finally, in the upper 10% quantile, we observe very strong responses to both output and inflation, and pronounced asymmetry in both cases. In fact, our results indicate that the long-run interest rate response to a unit positive inflation shock is approximately twice as large as the response to a unit negative shock. A similar pattern emerges in the case of output gap shocks. When we consider just these three quantiles, a clear pattern emerges that is consistent with MKT’s argument that policy aggression is a monotonically increasing function of $\kappa$.

FIGURE 6 ABOUT HERE

Overall, our results have two important implications. Firstly, as noted by MKT, policy does not become increasingly aggressive as the zero lower bound is approached; in fact, we observe the opposite. Secondly, by broadening our focus to the entire conditional distribution of the dependent variable, we are able to observe asymmetry where none was apparent when estimation was focused on the conditional mean. This suggests that the common practice of estimating at the conditional mean may obscure important underlying asymmetries.

5 Concluding Remarks

This paper identifies three fundamental forms of asymmetry that may characterise a dynamic economic process. Reaction asymmetry relates to the notion that the long-run response of the dependent variable to different types of shock to the same explanatory variable may differ. Adjustment asymmetry obtains when the path of dynamic adjustment of the dependent variable differs according to the nature of a shock to a given explanatory variable. Finally, locational asymmetry occurs when the response of the dependent variable to a given shock depends upon the conditional quantile of the dependent variable.

It follows that an easily implemented approach to modelling these three forms of asymmetry simultaneously and in a coherent fashion could be put to an abundance of uses. To this end,
we develop a quantile regression extension of the asymmetric ARDL framework advanced by Shin, Yu and Greenwood-Nimmo (2009). More specifically we specify a nonlinear conditional quantile function using the asymmetric ARDL functional form. Based on this structure, we can compute asymmetric cumulative dynamic multipliers with which to analyse response and adjustment asymmetries at the conditional quantile of interest. Moreover, we propose an array of hypothesis tests relating to each form of asymmetry in order to put the proposed modelling framework on a firm statistical footing.

Applying this technique to the analysis of US monetary policy, we find that the Federal Reserve responds linearly to both output and inflation in the lower quantiles of the interest rate. Moreover, in this range, the Fed does not adhere to the Taylor principle, indicating that monetary policy would not generally be considered stabilising in this region. We attribute this seemingly strange behaviour to the proximity of the zero lower nominal bound which seriously constrains the latitude enjoyed by policymakers in pursuit of their goals. Between the fortieth and eightieth quantiles, we find that the Taylor principle is upheld in the case of positive inflationary shocks but not in response to disinflationary shocks. Meanwhile, we note significant responses to both positive and negative output gap shocks, with a marked negative asymmetry. Hence, we conclude that the Fed acts as an inflation hawk in this region while also displaying a marked tendency toward growth-fostering policies. This combination of policies is potentially consistent with the opportunistic approach to monetary policy documented by Orphanides and Wilcox (2002). Finally, for the uppermost quantiles, we find evidence of very aggressive policy responses to positive and negative inflation and output gap shocks in the context of profound response asymmetry. Hence, our results support MKTs finding that the degree of policy aggression is an increasing function of $\kappa$.

Our results have a number of important implications for the conduct of monetary policy. Firstly, the finding that policy is relatively passive in the lowest quantiles suggests that the Fed has failed to pursue an optimal policy in the neighborhood of the zero lower bound, presumably for fear of encountering a liquidity trap. While the downside movement of the interest rate may be constrained in this case, a weak response by the Fed to positive inflation or output gap shocks is also intuitively plausible. At very low nominal interest rates, inflation is typically low (below the target) and the output gap negative in which case higher inflation and increasing output gap can be tolerated without running the risk of accelerating inflationary pressures or overheating the economy.

Another more general implication of our results is that the actions of the Fed become increasingly asymmetric as the interest rate increases. This may be an artefact of our dataset given that the majority of the interest rate observations that fall in the uppermost quantiles are associated with the Volcker Fed which was renowned for its anti-inflationary stance. Furthermore, cash flow constraints, that become more binding at high nominal interest rates (typically associated with high inflation rates), can provide a positive explanation why the Fed tends to react more strongly to negative output gap shocks (a strong aversion against recession) even at higher nominal interest rates.

Finally, we will close with a general observation regarding the combined modelling of various asymmetries. The failure of the NARDL-M model to reject the null hypotheses of reaction and adjustment symmetries leads us to believe that the common practice of confining one’s attention to the mean of the conditional distribution of the dependent variable may obscure important underlying effects. Hence, it follows that combination of the NARDL technique with quantile estimation (the NARDL-Q model) may provide profound insights into a range of, as yet, poorly understood economic phenomena.
References


### (A) Estimation Results

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### (B) Diagnostic and Inferential Test Statistics

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Note: $\chi^2_{SC}$ and $\chi^2_{HET}$ denote the Breusch-Godfrey LM test for serial correlation and the White LM test for heteroscedasticity. $W_{LR,\pi}$ refers to the Wald test of the restriction $\beta_\pi^+ = \beta_\pi^-$. By analogy, $W_{SR,\pi}$ and $W_{SR,y}$ are the Wald tests for additive adjustment asymmetry. The relevant 5% critical value of the $F_{PSS}$ test is 4.01 for $k = 4$ and 4.85 for $k = 2$.

Table 1: Estimation Results for the NARDL-M Model
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Table 2: Estimation Results for the NARDL-Q Model
Figure 1: Dynamic Multipliers for the NARDL-M Model: Inflation Shock

(a) LR & SR asymmetry

(b) LR asymmetry & SR symmetry

(c) LR symmetry & SR asymmetry

(d) LR & SR symmetry

Figure 2: Dynamic Multipliers for the NARDL-M Model: Output Gap Shock

(a) LR & SR asymmetry

(b) LR asymmetry & SR symmetry

(c) LR symmetry & SR asymmetry

(d) LR & SR symmetry
Figure 3: NARDL-Q Dynamic Multipliers of Positive Inflation and Output Gap Shocks
Figure 4: NARDL-Q Dynamic Multipliers of Negative Inflation and Output Gap Shocks
(a) Asymmetry: inflation shock

(b) Asymmetry: output gap shock

(c) Cross-sectional profiles of inflation asymmetry

(d) Cross-sectional profiles of output gap asymmetry

Figure 5: NARDL-Q Dynamic Multipliers - Asymmetry (i.e. the difference between Figures 3 and 4)
Figure 6: NARDL-Q Dynamic Multipliers: $\kappa = 0.1, 0.5, 0.9$. 

(a) Lower 10\% quantile - $\pi$ shock

(b) Lower 10\% quantile - $y$ shock

(c) 50\% quantile - $\pi$ shock

(d) 50\% quantile - $y$ shock

(e) Upper 10\% quantile - $\pi$ shock

(f) Upper 10\% quantile - $y$ shock