Structural FECM: Cointegration in large-scale structural FAVAR models

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Motivation

• Cointegration in factor-augmented VAR models:
  • FECM - Factor-augmented error-correction model - Banerjee and Marcellino (2009)
  • FECM outperforms the FAVAR and the standard error-correction model in forecasting - (Banerjee, Marcellino and Masten, 2013)

• This paper: Structural FECM - implications of cointegration in large systems of non-stationary variables

• Structural modelling in large systems
  • Bernanke, Boivin and Eliasz (2005) introduce the FAVAR
  • Stock and Watson (2005)
  • Forni, Giannone, Lippi and Reichlin (2009) - fundamentalness of structural representations
  • These and other similar applications work with I(1) data transformed to I(0)
  • Neglected potential cointegration between factors and variables
Contributions of this paper

- Derivation of the FECM from the DFM representation of non-stationary data
- Derivation of the moving-average representation of the FECM - extension of the Granger representation theorem
- Structural FECM: first discussion of long-run identification schemes for non-stationary DFMs
  - Forni et al. (2009), Stock and Watson (2005) - long-run identification in I(0) panel
  - Eickmeier (2009) - I(1) panel and sign restrictions
- Analysis of the importance of the error-correction mechanism in large panels through empirical examples and simulation experiments
Structure of presentation

- Basic idea of the FAVAR
- Representation of the Factor-augmented Error-Correction Model
- Structural analysis:
  - Identification with long-run restrictions
  - Identification with short-run/contemporaneous restrictions (omitted)
- Empirical applications
- Simulation experiments
- Conclusions
Consider that the economy is driven by $Y_t$ and $F_t$

- $Y_t$ observed, while $F_t$ unobserved by econometrician
- $Y_t$ and $F_t$ follow a VAR
- Many observed I(0) indicator variables $X_t$
- Assume factor structure

$$X_t = \Lambda^f F_t + \Lambda^y Y_t + e_t$$
FAVAR
BBE estimation

- Two approaches to estimation: likelihood-based Gibbs sampling or two-step approach with principal component analysis
- Two-step approach:
  - Estimate the space spanned by $Y_t$ and $F_t$ by PCA
  - Impose one of the factors to be observed and equal to the FFR, rotate the rest such that it is orthogonal to FFR, denote by $\tilde{F}_t$
  - Estimate the VAR for $[\tilde{F}_t', Y_t]'$, where FFR ordered last.
  - Estimate impulse responses of the FFR and factors
  - Regress each $X_{it}$ on FFR and rotated factors, plug in the IRs of factors and get IRs of $X_{it}$
# FAVAR - What do we get?

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<th>Variable</th>
<th>Graph</th>
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<td>CPI - I(1)</td>
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<td>3m TREASURY BILLS - I(0)</td>
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<td>AVG HOURLY EARNINGS - I(1)</td>
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<td>DIVIDENDS - I(0)</td>
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<td>CONSUMER EXPECTATIONS - I(0)</td>
<td>![Graph of CONSUMER EXPECTATIONS - I(0)]</td>
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</table>
Dynamic factor model for non-stationary data

\[ X_{it} = \sum_{j=0}^{p} \lambda_{ij} F_{t-j} + \sum_{j=0}^{m} \varphi_{il} c_{t-l} + \varepsilon_{it} \]

\[ = \lambda_i(L) F_t + \varphi_i(L) c_t + \varepsilon_{it}, \quad (1) \]

- Observables: \( X_{it}, i = 1, \ldots, N, i = 1, \ldots, T. \)
- \( T, N \) large.
- **Common trends** \( F_t \) - \( r_1 \)-dimensional vector of I(1) factors,
- **Common cycles** \( c_t \) - \( r_2 \)-dimensional vector of I(0) factors,
Dynamic factor model for non-stationary data

- $\lambda_i(L)$ - lag polynomial of order $p$,
- $\varphi_i(L)$ - lag polynomial of order $m$,
- $E(\lambda_i\varepsilon_{is}) = E(\varphi_i\varepsilon_{is}) = 0$ for all $t, i$ and $s$.
- Strict DFM assumption:
  - $\varepsilon_{it}$ is allowed to be serially correlated: $\varepsilon_{it} = \gamma_i(L)\varepsilon_{it-1} + \nu_{it}$,
  - $E(\varepsilon_{it}, \varepsilon_{js}) = 0$ for all $i, j, t$ and $s, i \neq j$.
  - Stock and Watson (2005): empirically rejected, but quantitatively of limited importance.
DFM in static form

• Note that

\[ \lambda_i (L) F_t = \lambda_{i0} F_t + \lambda_{i1} F_{t-1} + \cdots + \lambda_{ip} F_{t-p} \]

\[ = \tilde{\lambda}_{i0} F_t - \tilde{\lambda}_{i1} \Delta F_t - \cdots - \tilde{\lambda}_{ip} \Delta F_{t-p+1} \]

where

\[ \tilde{\lambda}_{ik} = \lambda_{ik} + \lambda_{ik+1} + \cdots + \lambda_{ip}, \quad k = 0, \ldots, p \]

• Define also

\[ \tilde{\Phi}_i = [\phi_{i0}, \ldots, \phi_{im}]' \]

and

\[ \Lambda_i = \tilde{\lambda}_{i0} \]

\[ \Phi_i = [-\tilde{\lambda}_{i1}, \ldots, -\tilde{\lambda}_{ip}, \tilde{\Phi}_i] \]

\[ G_t = \left[ c_t', c_{t-1}', \ldots, c_{t-m}', \Delta F_t', \ldots, \Delta F_{t-p}' \right]' \]
DFM in static form

\[ X_t = \Lambda_0 F_t + \Phi G_t + \varepsilon_t \quad (2) \]

- DFM in static form
- \( \varepsilon_t \) serially correlated
DFM in ECM form

- If we remove serial correlation from $\varepsilon_t$ we get

$$X_t = \Gamma (L) \Lambda_0 F_t + \Gamma (L) \Phi G_t + \Gamma (L) X_{t-1} + \nu_t \quad (3)$$

- With convenient factorization

$$\Gamma (L) = \Gamma (1) - \Gamma_1 (L) (1 - L) ,$$

- …and some manipulation we can obtain the DFM in ECM form

$$\Delta X_t = -(I - \Gamma(1))(X_{t-1} - \Lambda F_{t-1}) + \Lambda \Delta F_t + \Gamma_1 (L) \Delta F_{t-1} + \nu_t$$

Omitted in the FAVAR

$$\Phi G_t - \Gamma(1) \Phi G_{t-1} + \Gamma_1 (L) \Phi \Delta G_{t-1} - \Gamma_1 (L) \Delta X_{t-1} + \nu_t$$
The VAR process for factors

- $F_t$ are random walks
  \[ F_t = F_{t-1} + \varepsilon_t^F \]
- $c_t$ are stationary common cycles \(|\rho| < 1\)
  \[ c_t = \rho c_{t-1} + \varepsilon_t^c \]
- $\varepsilon_t^F$ and $\varepsilon_t^c$ are correlated invertible moving-average processes
- By inverting the moving-average processes for factor innovations, we get a conventional VAR for the factors
  \[
  \begin{bmatrix}
  F_t \\
  G_t
  \end{bmatrix}
  =
  \begin{bmatrix}
  M_{11}(L) & M_{12}(L) \\
  M_{21}(L) & M_{22}(L)
  \end{bmatrix}
  \begin{bmatrix}
  F_{t-1} \\
  G_{t-1}
  \end{bmatrix}
  + Q
  \begin{bmatrix}
  u_t \\
  w_t
  \end{bmatrix}
  \]
- $Q$ accounts for dynamic singularity of $G_t$
Estimation

- Our DFM uses the same (stricter) set of assumptions as Bai (2004)
- Number of $I(1)$ and total number of factors determined by criteria developed in Bai (2004) and Bai and Ng (2002)
- Space spanned by the $I(1)$ and $I(0)$ factors can be consistently estimated by principal components from the $I(1)$ data in levels
- Given strict DFM assumption remaining parameters estimated equation by equation.
- No generated-regressors problem (Bai, 2004) provided $N \gg T$
- With a simulation experiment we demonstrate that the method successfully retrieves the factor space and impulse responses even in small samples ($T, N < 50$)
Non-stationary data and the FAVAR

- FAVARs in Bernanke et al. (2005), Stock and Watson (2005) and Forni et al. (2009) are estimated on data differenced to I(0)
- Omission of the error-correction term:
  - Non-invertible MA component:
    \[ \Delta X_t = \Lambda_0 \Delta F_t + \Phi \Delta G_t + \Gamma (L) \Delta X_{t-1} + \Delta v_t \] (4)
  - Note that the error-correction term has a factor structure:
    - Omitted EC term can be proxied by inclusion of lags of I(0) factors - theoretically infinitely many
    - Problematic in applied work
- Empirical relevance: BBE dataset contains 120 series. 77 non-stationary. Loading to the EC term statistically significantly different from zero in 53 cases.
Moving average representation of the FECM

Granger representation theorem for the FECM

- Rewrite the factors VAR as

\[
\begin{bmatrix}
\Delta F_t \\
\Delta G_t
\end{bmatrix} = \begin{bmatrix}
0 \\
\alpha_M
\end{bmatrix} \begin{bmatrix}
0 & I_r
\end{bmatrix} \begin{bmatrix}
F_{t-1} \\
G_{t-1}
\end{bmatrix}
+ \begin{bmatrix}
M_{11}^*(L) & M_{12}^*(L) \\
M_{21}^*(L) & M_{22}^*(L)
\end{bmatrix} \begin{bmatrix}
\Delta F_{t-1} \\
\Delta G_{t-1}
\end{bmatrix} + Q \begin{bmatrix}
u_t \\
w_t
\end{bmatrix}
\]

- Combine with the error-correction representation of the DFM

\[
\Delta X_t = \tilde{a} \left( X_{t-1} - \Lambda F_{t-1} - \Phi G_{t-1} \right) + \Lambda \Delta F_t + \Phi \Delta G_t \\
+ \Gamma_1 (L) \left( \Lambda \Delta F_{t-1} + \Phi \Delta G_{t-1} \right) - \Gamma_1 (L) \Delta X_{t-1} + \nu_t, \quad (5)
\]
Moving average representation of the FECM

Granger representation theorem for the FECM

Then we can derive the GRT for the FECM as

\[
\begin{bmatrix}
X_t \\
F_t \\
G_t
\end{bmatrix} = \begin{bmatrix}
\Lambda \\
I_{r_1} \\
0_{r_2 \times r_1}
\end{bmatrix} \omega \sum_{i=1}^{t} u_t + C_1(L) \begin{bmatrix}
v_t + [\Lambda, \Psi]Q[u'_t, w'_t]' \\
Q[u_t] \\
Q[w_t]
\end{bmatrix}
\]

Common trends Stationary part

where

\[
\omega = \left[(I_{r_1} - M^*_1(1))\right]^{-1}
\]

has full rank
Identification of structural shocks based on long-run restrictions

- As is standard in SVAR analysis we assume that structural dynamic factor innovations are linearly related to reduced form innovations.

\[
\begin{bmatrix}
\eta_t \\
\mu_t
\end{bmatrix} = H \begin{bmatrix}
u_t \\
w_t
\end{bmatrix}
\]

- \(H\) is full-rank matrix
- \(\eta_t - r_1\) permanent structural dynamic factor innovations
- \(\mu_t - r_2\) transitory structural dynamic factor innovations.
Identification of structural shocks based on long-run restrictions

- From the MA representation we see that the permanent effects are
  \[ \Lambda \omega u_t \]

- Assume that the permanent effects of structural shocks are
  \[ \Lambda^* \omega^* \eta_t \]

- Consider identifying real and nominal shocks as in Blanchard and Quah (1990).
- Identifying restrictions: nominal shocks have no long-run effect on real variables
- King, Plosser, Stock and Watson (1991) apply this logic to the cointegrated VAR
- We extend to large \( N \)
Identification of structural shocks based on long-run restrictions

- Partition $X_t$ such that $N_1$ real variables ordered first, remaining $N_2 = N - N_1$ are ordered last.
- Assume $\Lambda^* \omega^*$ lower block diagonal, which implies ...
- ... both $\Lambda^*$ and $\omega^*$ lower block diagonal
Identification of structural shocks based on long-run restrictions

Estimation of $\Lambda^*$

- The restricted loading matrix $\Lambda^*$:

$$
\Lambda^* = \begin{bmatrix}
\Lambda_{11}^* & 0 \\
\Lambda_{21}^* & \Lambda_{22}^*
\end{bmatrix}
$$

- $\Lambda_{11}^*$ and $\Lambda_{21}^*$ estimated as loadings to the first factor - $F^r_t$ - extracted from the whole dataset

- Estimate the residuals $\varepsilon^r_t$ from a projection of $X_t$ on $F^r_t$.

- $\Lambda_{22}^*$ estimated as loadings to the $(r_1 - 1)$ factors $F^n_t$ - extracted from the lower $N_2$-dimensional block of $\varepsilon^r_t$. 
Identification of structural shocks based on long-run restrictions

Estimation of $\omega^*$

- From the factors VAR

$$\hat{\omega} = [(I_{r_1} - M^*(11))]^{-1}.$$  

- Estimate $\omega^*$ from the long-run covariance matrix

$$\omega E(u_t^F u_t^{F'}) \omega' = \omega^* E(\eta_t \eta_t') \omega^* \omega' = \omega^* \omega^*$$ \hspace{1cm} (6)

where $\eta_t = [\eta_t^{r'}, \eta_t^{n'}]'$ are the structural innovations and $\omega^*$ is lower block diagonal.
Empirical illustration

Data

- Extract 4 factors from data in levels (determined by information criteria of Bai (2004) and Bai and Ng (2002))
- Apply identification scheme from above
- Boostrapped 90% confidence intervals
Empirical example
Impulse responses to permanent real shock
## Effect of omitting the ECM term in the FAVAR

Percentage of FAVAR responses outside the FECM confidence intervals

<table>
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<tr>
<th>Variables</th>
<th>CI 12</th>
<th>24</th>
<th>36</th>
<th>48</th>
<th>60</th>
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Monte Carlo experiment

- Simulation experiment to analyse the effect of omitting the ECM term in the FAVAR
- Data generating process: FEVM estimated on 77 I(1) variables from BBE dataset
- Effect of:
  - Strength of error-correction: \( \alpha = [-0.25, -0.50, -0.75] \)
  - \( T \) dimension: \( T = [250, 500] \)
  - \( N \) dimension: \( N = [50, 100] \)
Monte Carlo results
Percentage of FAVAR responses outside the FECM confidence intervals

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Confidence interval coverage (%)

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<td>79.7</td>
<td>57.2</td>
<td>41.2</td>
<td>28.7</td>
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</table>

Average % of periods IRs outside confidence interval

<p>| | | | | | | | | | | |</p>
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<tbody>
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<td></td>
<td>50.4</td>
<td>36.4</td>
<td>47.9</td>
<td>35.6</td>
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<td>33.8</td>
<td>44.9</td>
<td>31.3</td>
<td>47.9</td>
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Conclusion

- This paper introduces the structural FECM
- We provide a generalization of the Granger representation theorem to large panels, which facilitates the analysis of structural shocks
- First application of the long-run identification scheme to cointegrated large-scale models
- Empirical and simulation evidence show that it is important to account for the error-correction mechanism in the FAVAR
- Responses to permanent real shocks compatible with DSGE evidence
Monetary policy shocks - FAVAR vs FECM

- FFR
- IP - I(1)
- CPI - I(1)
- 3m TREASURY BILLS - I(0)
- 5y TREASURY BONDS - I(0)
- MONEY BASE - I(1)
- M2 - I(1)
- EXCH RATE YEN - I(1)
- COMMODITY PR IND - I(1)
- CAPACITY UTIL RATE - I(0)
- PERSONAL CONS - I(1)
- DURABLE CONS - I(1)
- NONDURABLE CONS - I(1)
- UNEMPLOYMENT - I(0)
- EMPLOYMENT - I(0)
- AVG HOURLY EARNINGS - I(1)
- HOUSING STARTS - I(0)
- NEW ORDERS - I(0)
- DIVIDENDS - I(0)
- CONSUMER EXPECTATIONS - I(0)