1 HP97

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in SSF using the

The ~~F~~ilter of Hodrick and Prescott (1997, HP-Filter) can be expressed ~~as an SSM~~ following

HP0 ~~a~~ UC model structure as:

unobserved component (UC) model

$$y_t = y_t^* + y_t^c \quad (1a)$$ HP0a

$$\Delta^2 y_t^* = \varepsilon_{1t} \quad (1b)$$ HP0b

$$y_t^c = \phi \varepsilon_{2t}, \quad (1c)$$ HP0c

where y_t is (~~generally~~ 100 times) the log of GDP, and ε_{1t} and ε_{2t} are $N(0,1)$. The standard deviation ϕ is the (square root of the) smoothing parameter, generally set to 40, for quarterly data implying a value of 'λ' of 1600.

The number shock to named shock mapping is:

$$\begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \end{bmatrix} = \begin{bmatrix} \varepsilon_t^* \\ \varepsilon_t^c \end{bmatrix} \quad (2)$$

, where ε_t^* is the trend or permanent shock and ε_t^c is the cycle or transitory shock.

2 Shock recovery SSM

2.1 SSM with lagged states

SSM Kurz's (2018) SSM has the following general from:

$$\text{Measurement}: \quad Z_t = D_1 X_t + D_2 X_{t-1} + R\varepsilon_t \quad (3a)$$ ssm1

$$\text{State}: \quad X_t = A X_{t-1} + C\varepsilon_t, \quad (3b)$$ ssm2

where $\varepsilon_t \sim MN(0, I_m)$, D_1, D_2, A, R are C are conformable system matrices, Z_t the observed variable and X_t the latent state variable.

2.2 HP97 SSM for shock recovery

To assess recovery, re-write the UC model in (1) in '*shock recovery*' ~~State Space Form~~ $\boxed{\text{(SSF)}}$. That is, collect all observables in Z_t and all shocks (and other state variables) in X_t to yield:

rearrange (1) to

on the LHS in Z_t

$$\begin{aligned} \Delta^2 y_t &= \Delta^2 y_t^* + \Delta^2 y_t^c \\ &= \varepsilon_{1t} + \phi \Delta^2 \varepsilon_{2t} \\ &= \varepsilon_{1t} + \phi \varepsilon_{2t} - 2\phi \varepsilon_{2t-1} + \phi \varepsilon_{2t-2}, \end{aligned} \quad (4)$$ Z

where $\Delta^2 y_t$ ~~$= Z_t$~~ is the only observed variable.

Note: The estimates of the shocks from the Kalman Filter $E_t X_t = E_t \begin{bmatrix} \varepsilon_t & \varepsilon_{2t} & \varepsilon_{2t-1} \end{bmatrix}'$ will

ε_{1t}

move this down

be linked by the identity:

$$E_t\varepsilon_{2t} = \phi E_t\varepsilon_{1t}$$

and from the Kalman Smoother $E_T X_t = E_T \begin{bmatrix} \overset{\varepsilon_{1t}}{\varepsilon_t} & \varepsilon_{2t} & \varepsilon_{2t-1} \end{bmatrix}'$ by the identity:

$$\Delta^2 E_T\varepsilon_{1t} = \frac{1}{\phi^2} E_T\varepsilon_{2t-2}. \tag{5}$$ KS

With $\varepsilon_{1t} = \Delta^2 y_t^*$ and $\varepsilon_{2t} = \frac{1}{\phi^2} y_t^c$, this means that the output from the standard HP–Filter will give the identity:

$$\begin{aligned} \Delta^4 y_t^* &= \frac{1}{\phi^2} y_{t-2}^c \\ \Delta^4\text{HP–trend}_t &= \frac{1}{\phi^2}\text{HP–cycle}_{t-2}. \end{aligned}$$

Indeed, running a regression of Δ^4HP–trend$_t$ on HP–cycle$_{t-2}$ (without an intercept) yields a regression coefficient of $0.000625 = 1/1600$ when applied to US–GDP data that was HP–Filtered with the smoothing parameter set to $\lambda = 1600 = 40^2$. The regression fit is perfect, with an R^2 of 1 and a residual sum of squares of 0.

KOSSM The Measurement and State equations corresponding to (4) are:

$$\begin{aligned} \text{Measurement}: \quad Z_t &= D_1 X_t + D_2 X_{t-1} + R\varepsilon_t \\ &= \varepsilon_{1t} + \phi\varepsilon_{2t} - 2\phi\varepsilon_{2t-1} + \phi\varepsilon_{2t-2} \end{aligned} \tag{6a}$$

$$Z_t = \underbrace{\begin{bmatrix} 1 & \phi & 0 \end{bmatrix}}_{D_1} \underbrace{\begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \\ \varepsilon_{2t-1} \end{bmatrix}}_{X_t} + \underbrace{\begin{bmatrix} 0 & -2\phi & \phi \end{bmatrix}}_{D_2} \underbrace{\begin{bmatrix} \varepsilon_{1t-1} \\ \varepsilon_{2t-1} \\ \varepsilon_{2t-2} \end{bmatrix}}_{X_{t-1}} + \underbrace{\begin{bmatrix} 0 & 0 \end{bmatrix}}_{R} \underbrace{\begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \end{bmatrix}} \tag{6b}$$

$$\text{State}: \quad X_t = AX_{t-1} + C\varepsilon_t,$$

$$\underbrace{\begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \\ \varepsilon_{2t-1} \end{bmatrix}}_{X_t} = \underbrace{\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} \varepsilon_{1t-1} \\ \varepsilon_{2t-1} \\ \varepsilon_{2t-2} \end{bmatrix}}_{X_{t-1}} + \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}}_{C} \underbrace{\begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \end{bmatrix}}_{\varepsilon_t}. \tag{6c}$$