Smoothed Effective Amplitude Spectrum (EAS) as a Metric for GM Modeling Using FAS

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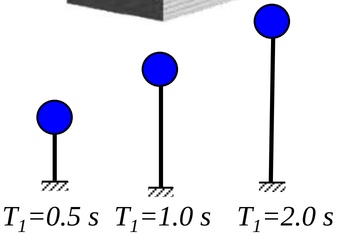
Motivation: FAS-based GMM

- The response spectrum is the standard
  - For design: correlates well with structural response
  - Output of GMM/GMPE
- The response spectrum depends on the characteristics of single-degree-of-freedoms of different frequencies



- NGA-East data: limited bandwidth, limited (M, R) coverage, requires site and kappa correction to hard rock
- Develop GMM in Fourier Amplitude Spectrum (FAS)
  - Better representation of seismological effects (source, site, etc.)
  - Modifications applied as factors directly (k_0, site effects, etc.)
  - Allows to handle limited bandwidth
- Use Random Vibration Theory (RVT) to compute response spectra from FAS for the final model

RVT Components

Random vibration theory defines a motion by its power spectral density, computed from:

- Frequency content: Fourier amplitude spectrum, A(f)
- Stationary duration: D of constant statistical properties

Expected values (peak factors) in the time domain are computed using extreme value statistics

Response of a system (oscillator, site, structural) can be computed by applying the appropriate transfer function.

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RVT Computation Steps

1. Compute FAS (*A(f)*), apply transfer function (optional)
2. Compute root-mean-squared acceleration:

$$a_{rms} = \sqrt{m_0 / D_{gm}}$$

D_{gm} is the ground motion duration
m_0 is the 1st spectral moment of FAS:

$$m_k = 2\int_0^{\infty} (2\pi f)^k \left|A(f)\right|^2 df$$

3. Compute peak factors (PF)
4. Obtain time domain peak value ($a_{max} = PF \times a_{rms}$)

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FAS-RVT Considerations

- Development of GMM needs
  - Appropriate PF for RS, but also for other effects (site, kappa, etc.)
  - Orientation-independent FAS spectrum definition that maintains power
  - Reduced frequency spacing to a reasonable number while maintaining appropriate characteristics of RVT for RS computations (smoothing)
  - Appropriate duration calibrated to match TD-RS

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Peak Factors (PF) components

- The spectral motions are used to define the frequency of zero crossings by:

$$f_z = \frac{1}{\pi}\sqrt{\frac{m_2}{m_0}}$$

- and the number of zero crossings by:

$$N_z = f_z \cdot D_{\mathrm{gm}} = \frac{1}{\pi}\sqrt{\frac{m_2}{m_0}} \cdot D_{\mathrm{gm}}$$

- Similarly, the frequency and number of extrema can be computed by:

$$f_e = \frac{1}{\pi}\sqrt{\frac{m_4}{m_2}} \qquad N_e = f_e \cdot D_{\mathrm{gm}} = \frac{1}{\pi}\sqrt{\frac{m_4}{m_2}} \cdot D_{\mathrm{gm}}$$

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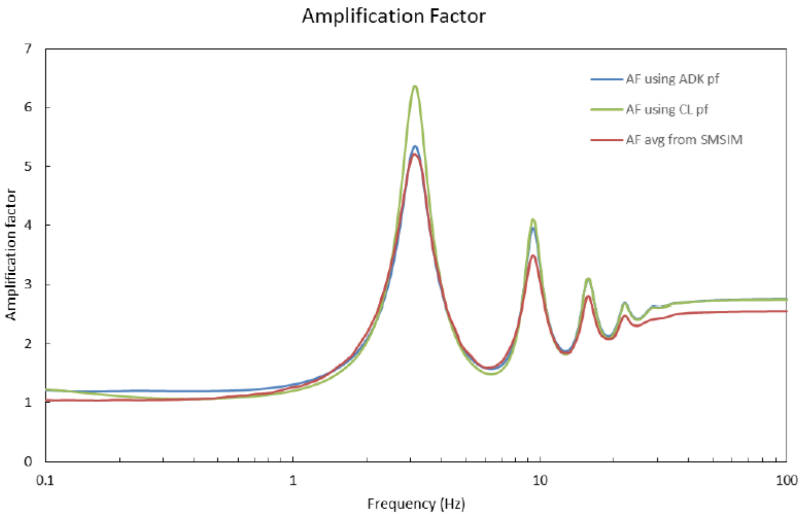
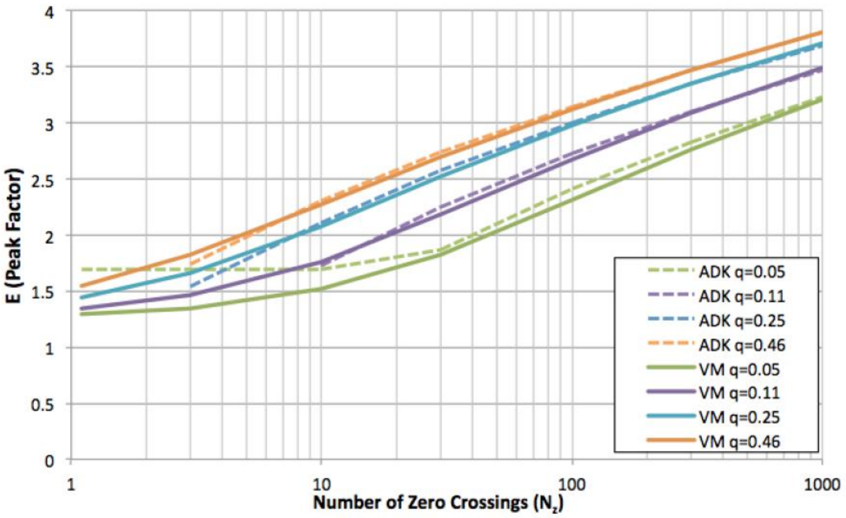
Peak factor Formulations

- Defines the distribution of peaks based on spectral moments of the ground motion
- A few of the peak factor formulations considered:
  - Cartwright and Longuet-Higgins (1956)
  - Vanmarcke (1975)
  - Der Kiureghian (1980)
- General assumptions:
  - band-limited white Gaussian noise with zero mean
  - stationary stochastic process over duration interval
  - random phase angles

RVT PF Evaluations



Kottke and Rathje (2013) observed better agreement between TD and ADK RVT for site response than for CL RVT.



Better low frequency representation from VM RVT than ADK (Rathje, pers. comm.)

Selected the Vanmarcke (1975) PF for NGA-East GMM development (PEER 2015/04, Ch. 11)

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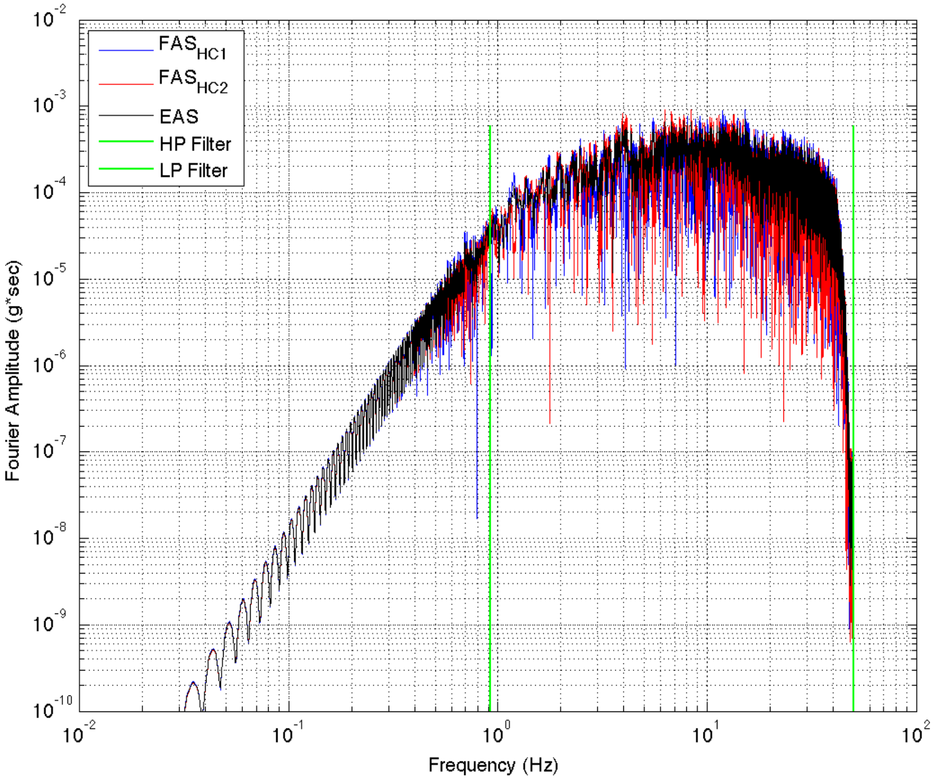
Orientation-independent FAS

- Effective Amplitude Spectrum (EAS)

$$EAS(f) = \sqrt{\frac{1}{2}\left[A_{H1}(f)^2 + A_{H1}(f)^2\right]}$$

Average performed in A^2 to maintain power (Boore, 2003)



Smoothing of FAS

- Goal: maintain power $A(f)^2$ (and properties relevant to RVT) while reducing the number of data points
- Find common df for dataset so that smoothing is consistent between records

NGA-East Data	Type 1	Type 2
sps	10, 20, 40	50, 100, 200
dt	0.1, 0.05, 0.025	0.02, 0.01, 0.005
Dur (s)	3276.8	2621.44
Power of 2	15, 16, 17	17, 18, 19
Δf	0.00030518	0.0003815

Smoothing of FAS

- Considered various schemes and performed sensitivity studies:
  - linear (Hamming windows of varying widths)
  - logarithmic (Konno-Ohmachi 1988)

- Konno-Ohmachi provides better $A(f)^2$ representation and stronger even smoothing over all bandwidths, but complicates statistics

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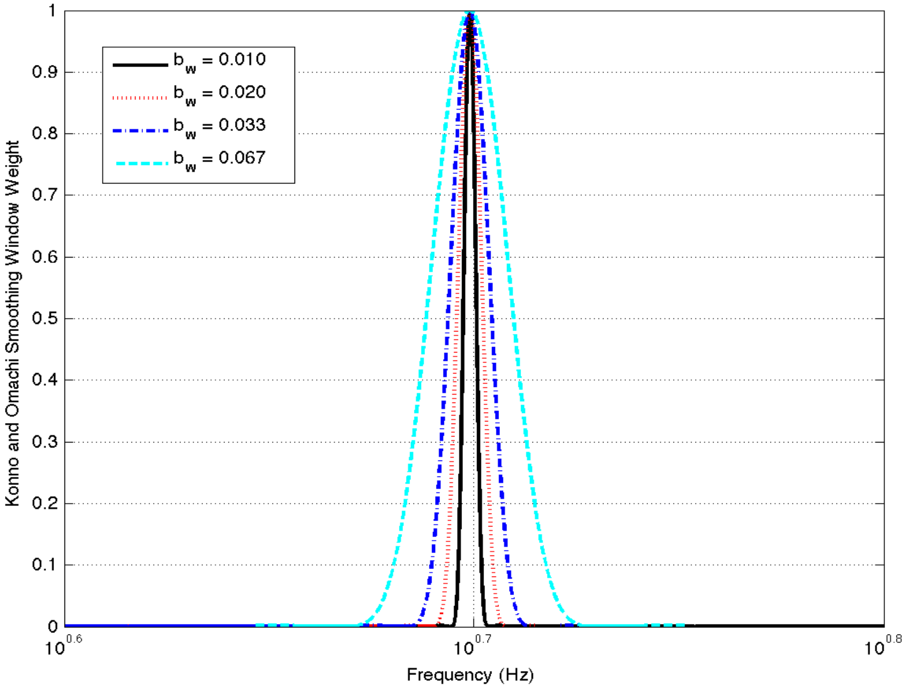
Konno and Ohmachi (1988) Weighting Window

$$W = \left(\sin\left[\frac{2p}{b_w} \log\left(f / f_c\right) \right] / \left[\frac{2p}{b_w} \log\left(f / f_c\right) \right] \right)^4$$

b_w:bandwidth of smoothing window in log10 units



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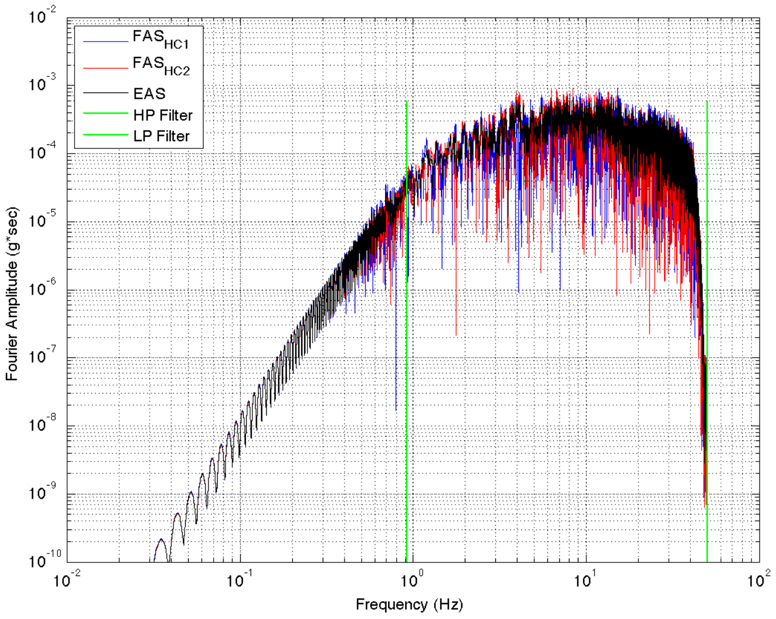
Percentage of records in NGA-EAST database (10k records) that have RVT properties of the smoothed and down-sampled EAS within ±1% of the RVT properties of original EAS.

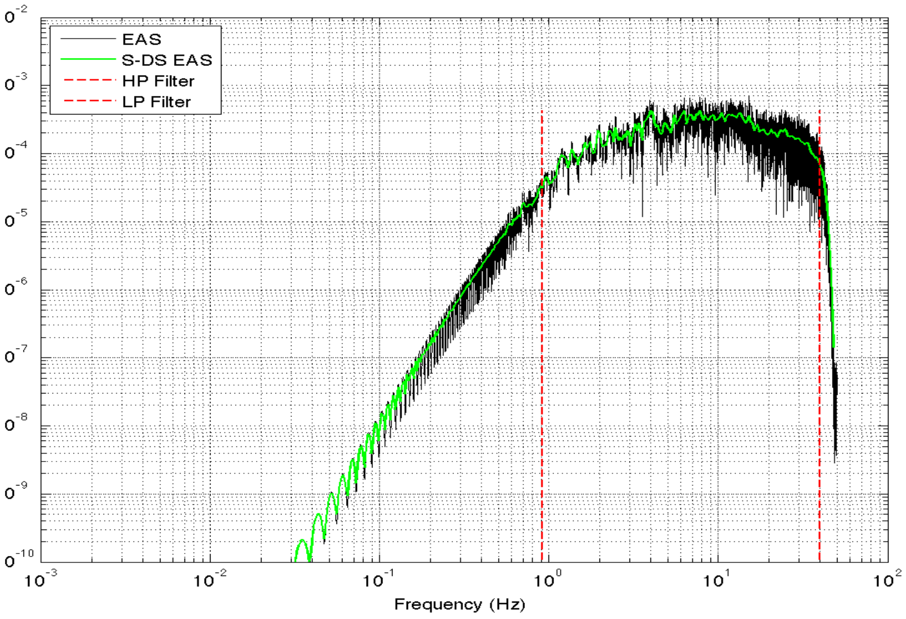
Oscillator Period = 10sec					
Frequency Points per Decade	Width of Smoothing window, b_w	m0	q	fz	fe
30	1/15	22%	37%	60%	76%
30	1/30	11%	14%	32%	37%
50	1/30	30%	34%	63%	70%
50	1/50	19%	19%	40%	43%
100	1/30	94%	99%	99%	100%
100	1/100	37%	28%	58%	56%

Oscillator Period = 0.2sec					
Frequency Points per Decade	Width of Smoothing window in fraction of a decade	m0	q	fz	fe
30	1/15	21%	15%	87%	92%
30	1/30	12%	10%	66%	78%
50	1/30	25%	24%	89%	94%
50	1/50	14%	13%	73%	83%
100	1/30	99%	98%	100%	100%
100	1/100	17%	15%	79%	88%

Oscillator Period = 0.01sec					
Frequency Points per Decade	Width of Smoothing window in fraction of a decade	m0	q	fz	fe
30	1/15	46%	49%	86%	88%
30	1/30	18%	20%	47%	57%
50	1/30	35%	39%	80%	85%
50	1/50	19%	21%	54%	63%
100	1/30	99%	98%	100%	99%
100	1/100	24%	26%	64%	70%

Example of smoothed EAS spectrum





Cap-Rouge (Quebec) 1997 M4.45 earthquake, A11 station

Conclusions

- For FAS-based GMM development, we recommend the VanMarcke 1975 peak factors, to be used with empirically calibrated durations
- Smoothing on the EAS using the KO (1988), using 100 pts per decade and a b_w of 1/30 allows to minimize artifacts affecting RVT computations for RS
- PEER report 2018/XX to be released soon
- FAS computed for NGA-East, NGA-West2 and NGA-Sub use those recommendations

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VanMarcke (1975) Peak Distribution

Cumulative distribution of peak values defined by:

$$F_x(x) = \left[1 - \exp\left(\frac{-x^2}{2}\right)\right] \cdot \exp\left\{\frac{-N_z\left[1 - \exp\left(-\sqrt{\pi/2}\cdot\delta_e\cdot x\right)\right]}{\exp\left(\frac{x^2}{2}\right) - 1}\right\}$$

where δ_e is defined as:

$$\delta_e = \delta^{1+b} = \left[1 - \frac{m_1^2}{m_0 \cdot m_2}\right]^{(1+b)/2}$$

and b is empirically calculated to be 0.2

Expected peak factor computed by:

$$E[x] = \int_0^\infty [1 - F_x(x)]dx$$

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