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ESTIMATION OF NON-LINEAR SITE AMPLIFICATION USING DOWNHOLE RECORDINGS

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SUMMARY

Data from seven downholes in Japan are used to investigate strain dependent site amplification. The frequency-dependent transfer function of site is calculated as a ratio of spectrum at uphole to the spectrum at downhole, considering the horizontal component of shear waves. The reduction in the predominant frequency and amplification factor with increases in excitation level reflects the non-linear site response. While the trend of predominant frequency decreasing with the excitation level is clear for all the sites, the amplification factor trend is misleading and inconsistent with laboratory results. The results are then discussed with respect to uncertainties and biases associated with the amplification factor estimates using spectral ratio technique.

INTRODUCTION

Weak and strong motion analysis facilitates investigation of actual linear and non-linear soil responses, which is one of the important topics in earthquake engineering. It has been known in geotehcnical engineering that the soil response becomes non-linear beyond a certain level of deformation. Stress-strain relationships in the range of shearing deformation produced by large earthquakes are non-linear and hysteric, as confirmed by numerous results of vibratory loading test around the world. However, the non-linear soil behaviour, which is postulated geotechnically, depends on the big assumption that the in-situ materials behave similarly. On the other hand, there is a few evidence of non-linearity by using actual strong ground motions (Wen et al. 1995, Ghayamghamian and Kawakami 1996). Therefore, the actual non-linear response of the soil to large earthquakes, which plays an important role for hazard mitigation, remains unclear. In spite of this, non-linear effects have been routinely taken into account in the evaluation of seismic amplification by superficial deposits. Unfortunately, there is no complete and practical quantification of these phenomena from actual data that remains the problem in this stage of developments.

The methods for determining dynamic characterisation of surface layer are mostly based on spectral ratio analysis. In spectral ratio analysis, due to the effects of the noise, both numerator and denominator spectra should be smoothed using various types of windowing techniques. There are no specific rules for the window function, where noisy records (small signal-to-noise ratio) need more smoothing (i.e. need larger window length and/or successive smoothing). This may obscure the exact resonance frequency and amplification factor of the site.

Here, an attempt is made to clarify the problem in identification of non-linear amplification by spectral ratio analysis using downhole recordings. Downhole data in non-linear study is favourable since the problem of source and path spectral contributions, which are a main obstacle to identifying non-linear site effects using the spectral ratio of one site to that of reference site, can be strongly overcome (Wen et. al. 1995). This is due to the fact that the distance between uphole and downhole instruments is negligible for the source radiation and the wave propagation path effects, which often overshadow the non-linearity. Hence, it is interesting to study different aspects of soil amplification to strong and weak motions.

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SITE CONDITION AND EARTHQUAKE DATA

Seven Japanese sites with downhole accelerographs are considered in this study. Their location and detailed descriptions of soil parameters for the sites, which the geotechnical and geophysical field exploration have been carried out, are given in the previous paper by the authors and will not be given here due to space limitation (Ghayamghamian and Kawakami 1996, Fig. 1 and Tables I). In each site, the three components of acceleration are installed at different depths. The NS component of acceleration in depths of 10, 100, 30, 40, 28, 100 and 44m is used in Chiba, Etchujima, Fujisawa, Samukawa, Shinfuji, Tomioka and TTRL sites respectively for spectral ratios presented here. The data was recorded digitally at the rates of 100, 200 or 500 samples per second. The analysed earthquakes are selected from Strong Motion Array Recorded database in Japan published by Association for Earthquake Disaster Prevention (DACWS 1992 and 1993, Katayama et. al. 1990).

The smallest and biggest possible earthquake data has been selected for each site. On the contrary, only the largest earthquakes with, 170 and 130 gals (cm/s2) surface PGA (Peak Ground Acceleration) are used for Samukawa and Tomioka sites respectively. The length of the recordings at these sites makes it possible to derive the transfer function of weak motion by using the ending parts of the records. Parameters of the events selected for the analysis are listed in Table II of previous paper by the authors (Ghayamghamian and Kawakami 1996). The surface PGA of strong motions extended from 80 to 416 gals. Figure 1 shows some examples of recorded events at uphole and downhole in Chiba and Fujisawa sites.

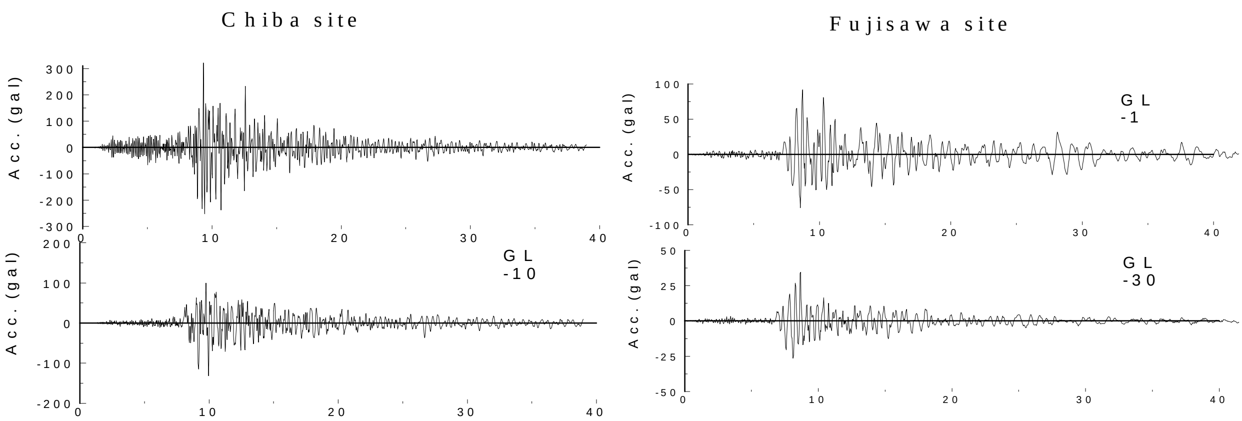

Figure1: Uphole and downhole Accelerograms in the NS direction for events 3 and 9

NON-LINEAR AMPLIFICATION FACTOR

The surface layer overlying a rigid basement exhibits the predominant resonance frequency, *f*, at $f=v_1/4h$, where v_1 is the shear wave velocity of the surface layer, and h is the thickness. The amplification at resonance is expressed as $2/\alpha$, in which α is the impedance ratio defined as $\rho_1 v_1/\rho_2 v_2$ and ρ is density. Thus, the resonance frequency and amplification factor of the layer is proportional to the wave velocity and will be decreased as the strain increases. Because of this proportional relationship, the non-linear soil response can be investigated in the form of reduction in resonance frequency and amplification factor of the soil system with increases in the level of motion. Consequently, if an earthquake is divided to several time windows (i.e. different levels of shaking), the reduction in resonance frequency of soil transfer function should be seen as the level of shaking increases in those time windows.

The transfer function of soil can be obtained by spectral ratio of uphole to downhole for different time windows of the record. Then, accelerograms recorded at uphole and downhole were divided into a number of 10.24s or 5.12s time windows (with 1024 data points) representing different levels of shaking. The time window divisions were used between the S-wave arrival and, generally, the end of the record. In spectral analysis, autospectrum is employed.

The spectral ratio is calculated using the following procedure for each time window: (1) The autospectrum for uphole and downhole motions is calculated; (2) the spectra are smoothed using moving average filter having a band width of approximately 0.5 Hz; (3) the ratio of two smoothed spectra is calculated; (4) the square root is taken from spectral ratio. Three times consecutive smoothing were applied to the raw spectra. This number was chosen empirically considering its visual effect on the spectral shape.

Figure 2 shows some identified transfer functions of the sites. From this figure, the downward shift in predominant resonance frequency can be clearly seen. However, the decrease in amplification factor with respect to the excitation level is inconsistent. For instance, while Fujisawa site shows clear decrease in amplification factor with 91 gal PGA, Chiba site shows no clear decrease in amplification factor with 301 gal PGA. In previous study, authors studied the decrease in predominant resonance frequency with respect to excitation level in more details and this object would not be addressed in this study (Ghayamghamian and Kawakami 1996). Here, an attempt is made to answer the inconsistency in the result of amplification factor with excitation level for the sites. Figure 3 shows amplification factors for different time windows of events at the sites versus maximum

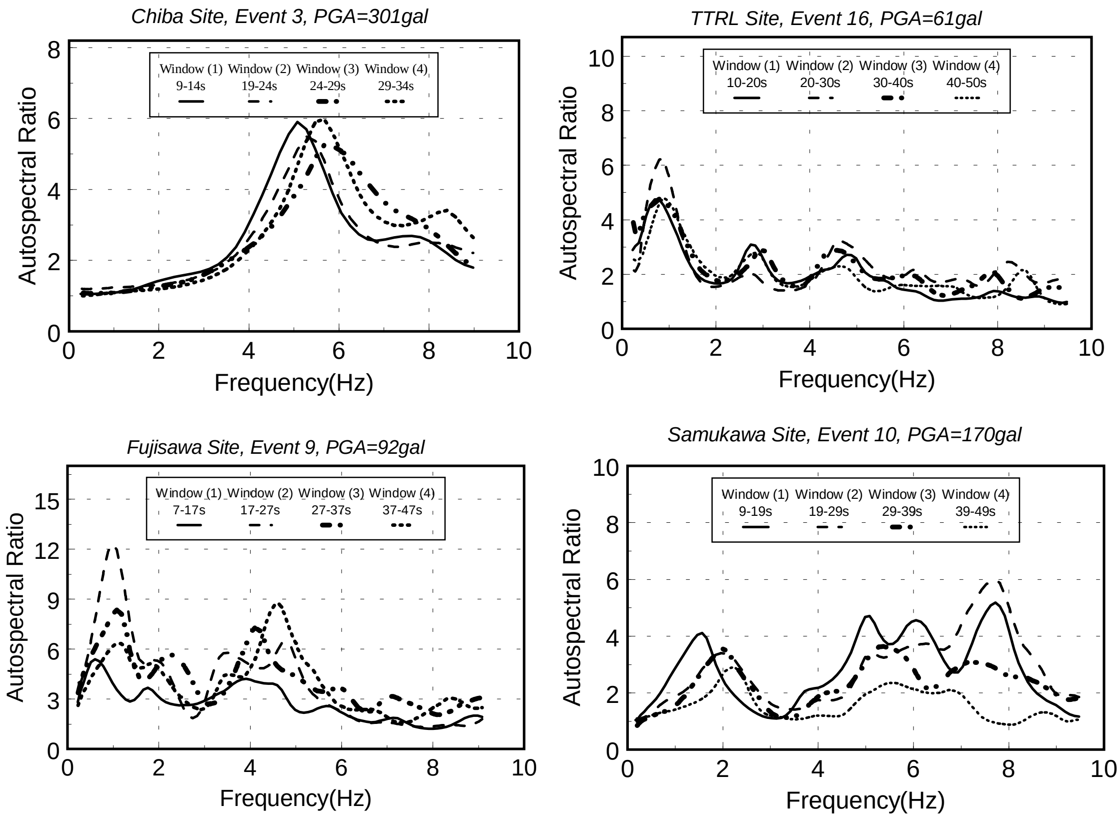

Figure 2: The identified transfer functions for different time widows of events 3 and 9

acceleration at down hole for those windows. Figure 4 shows the same values versus maximum strains. The strain is calculated by two times integration from accelerographs at uphole and downhole divided by their distance. The base line correction is also applied in the calculations. As can be seen from this figure, there is no clear trend of deamplification effect in spectral ratios of different time windows at the sites. The reason for this inconsistency is given in the next section.

SMOOTHING EFFECT

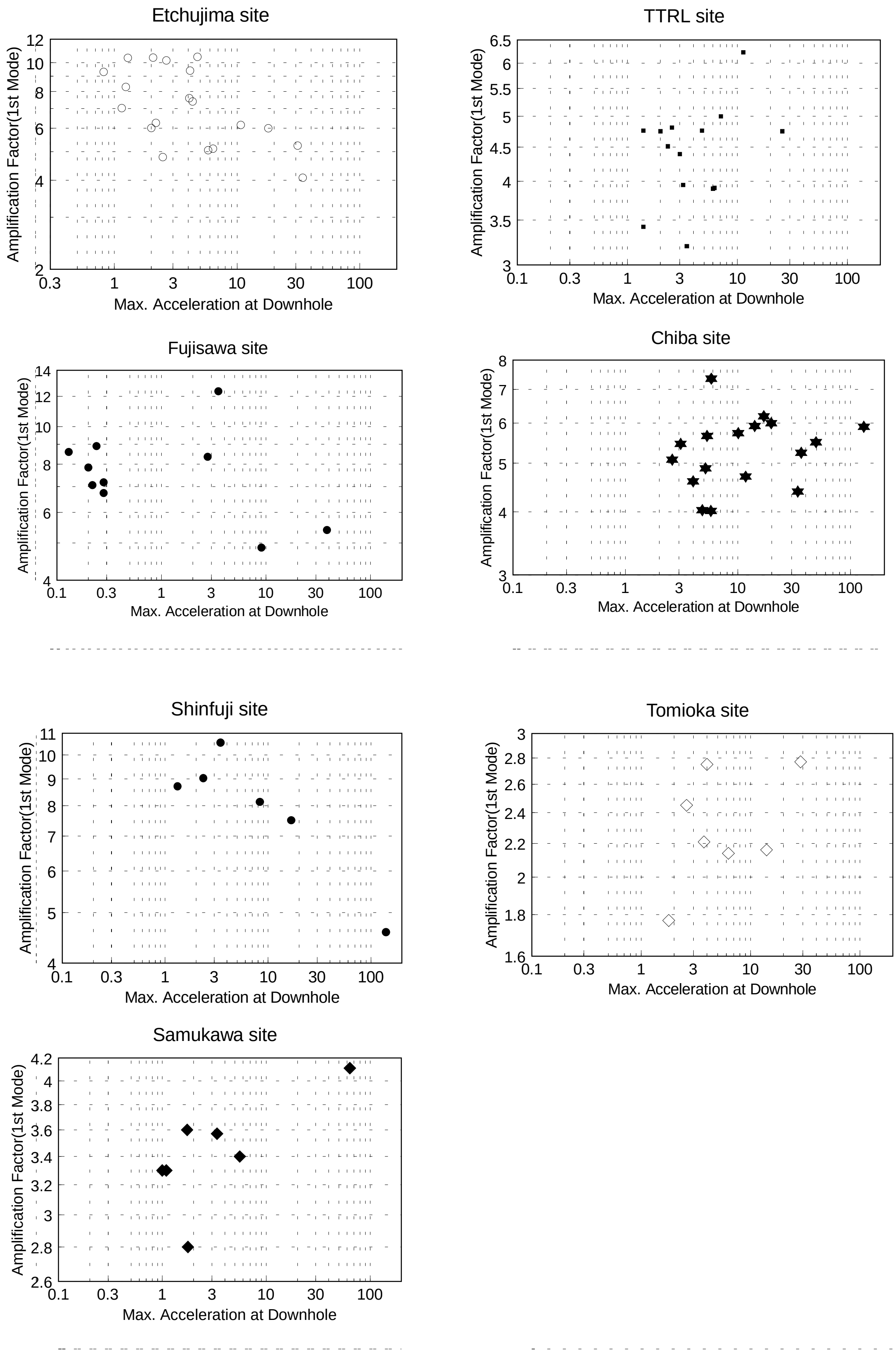

Figure 3: The identified amplification factor for time windows of the events versus maximum acceleration at downhole

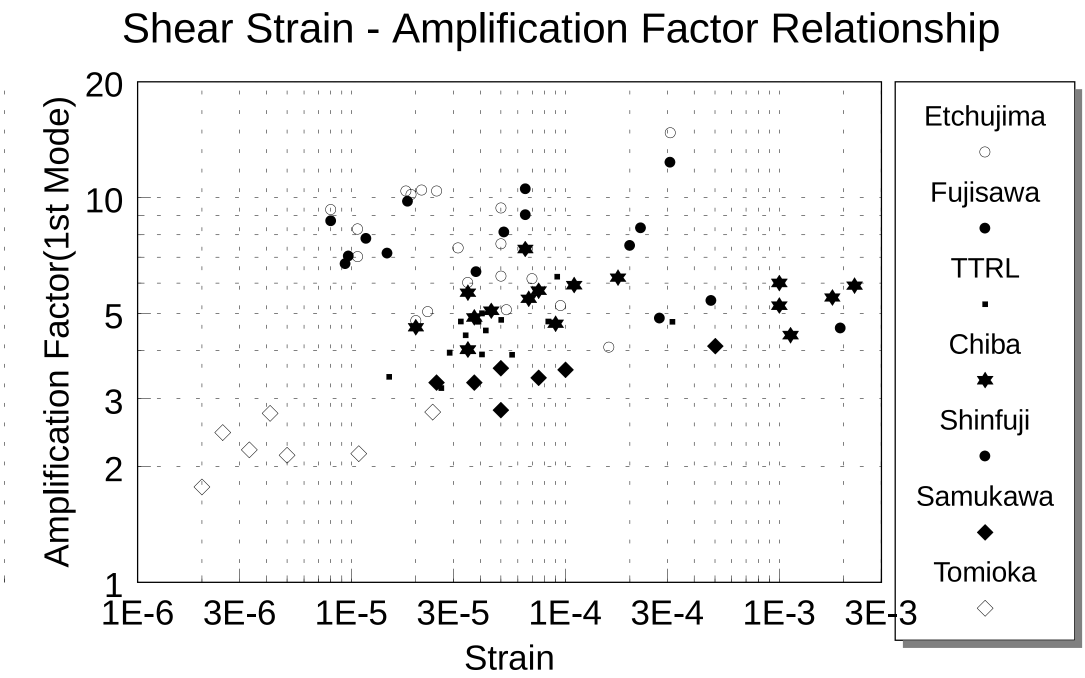

Figure 4: The identified amplification factor for time windows of the events versus maximum acceleration at downhole

The methods for determining dynamic characterisation of surface layer are mostly based on spectral ratio analysis. In spectral ratio analysis, due to the effects of the noise, both numerator and denominator spectra should be smoothed using various types of windowing techniques. There are no specific rules for the window function, where noisy records (small signal-to-noise ratio) need more smoothing (i.e. need larger window length and/or successive smoothing). This may obscure the exact resonance frequency and amplification factor of the site. This major problem in site identification using spectral ratio analysis is clarified using the following numerical analysis.

Numerical Analysis

The effects of noise and smoothing on amplification factor of the soil system are investigated. Analysis is carried out using the response of earthquake motions to a simple soil model. Figure 5 shows the soil model and its analytical transfer function. The model is subjected to earthquake data from Chiba site as an input motion in the base layer (events 1 and 2). A computer program is developed to calculate the output at the soil surface. In the computer code, vertical propagation of shear waves through the linear viscoelastic soil system is considered. Noise effects are considered by adding a different white noise to input and output motions. The transfer function of soil is calculated based on Fourier spectral ratio of output to input motions. In order to show the effect of smoothing on calculated transfer functions, moving average spectral window with 3 and 5 samples width is successively applied. The calculated transfer functions are shown in Figure 6. This figure demonstrates the effects of smoothing on the evaluation of amplification factor. As the number of successive smoothing or the samples under the smoothing window increases, the bias in estimation of amplification factor also increases.

This is the main disadvantage of site identification using spectral analysis in frequency domain. This could explain the reason of inconsistency between the results of actual recordings and theoretical hypothesis for identification of non-linear soil response using calculated amplification factors of the sites shown in Figure 2. It should be also noticed that the error is more significant for the amplification factor than it is for the resonance frequency. This is an explanation for the reason of consistency between the results of actual recordings and theoretical one for identification of non-linear soil response using calculated resonance frequency (Ghayamghamian and Kawakami, 1996, Fig. 9).

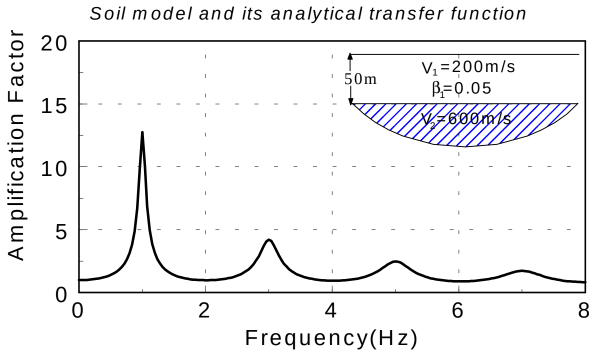

Figure 5: Simple soil model and its analytical transfer function assumed for numerical analysis

In identification of transfer function, the same window type and length were applied in the analysis as explained above for all the sites. This may lead one to the hypothesis that the effect of smoothing is same for all identified amplification factors at each site and the trend of deamplification could be revealed. However, it should be noticed that the effect of smoothing would be higher for a peak with narrow width and high value than it is for the peak with wide width and low value. This fact will lead the results to an unsystematic error in estimation of amplification factor, which can not refine the actual trend of amplification values with level of excitation.

CONCLUSIONS

In this study, the problems associated with non-parametric system identification are discussed. Non-parametric procedures evaluate the transfer function of the system in frequency domain using spectral ratio technique. This transfer function is computed from smoothed auto or cross- spectral density functions of the input and output motions, and represents an estimate of output-to-input motion in the frequency domain. Modal frequencies and amplification factors are estimated from peaks in the transfer function. The non-parametric procedure was used to identify non-liner soil response in seven vertical arrays in Japan. The soil transfer function is identified using smoothed autospectral ratio of output-to-input motion. The decreases in resonance frequencies and amplification factors with increases in excitation level or strain reveals the non-linear response of the soil. In spite of the evident shifting in the resonance frequencies with the level of the shaking, there is no clear trend of deamplification effect in spectral ratios of different time windows for each earthquake at the sites. An attempt is made to clarify this inconsistency between the results. It is shown that the determination of vibration frequencies and amplification factors from non-parametric procedures can be problematic, as the shape of transfer function is dependent on the method of estimating the spectral density functions and, especially, windowing procedure. It is clarified that the error in estimation of amplification factor is higher than the resonance frequency. This is an explanation to the fact that why the non-linear soil response can be followed by identified resonance frequency relation with level of excitation and can not be followed by amplification factor relation with excitation level. Therefore, the large bias in estimation of amplification factor due to smoothing procedures is introduced as a main disadvantage of system identification by spectral analysis in frequency domain.

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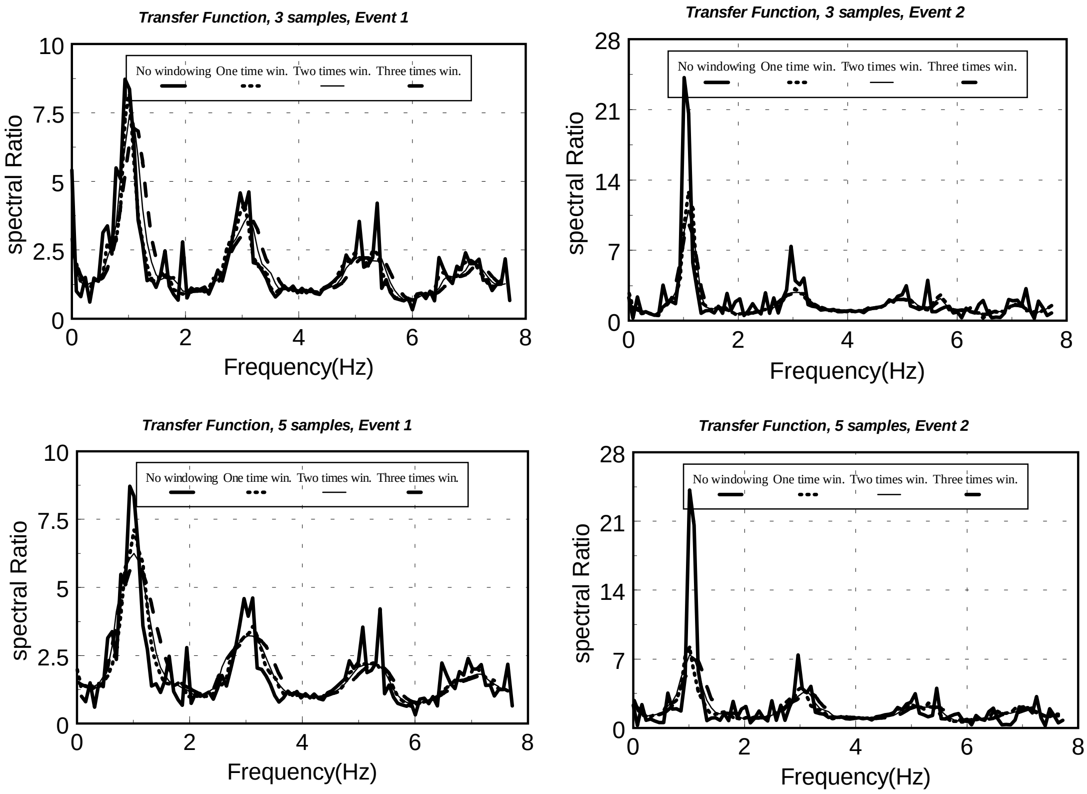

Figure 6: Effect of smoothing on identified transfer function

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