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THEORETICAL DEVELOPMENT FOR LOW DISTORTION BROADBANDING OF SEISMIC DATA

Lewis J. Pinson, et al

ENSCO, Incorporated

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ENSCO, INC.
5408A Port Royal Road
Springfield, Virginia 22151
Phone: (703) 569-9000

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THEORETICAL DEVELOPMENT FOR LOW DISTORTION BROADBANDING OF SEISMIC DATA-INTERIM TECHNICAL REPORT

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ENSCO, INC.
8001 Forbes Place
Springfield, Va. 22151

Technical Director

Richard L. Sebastian
Director, ISS Division

L. J. Pinson
Principal Investigator

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13. ABSTRACT

A "soft" zero-memory non-linearity is modeled to demonstrate effects of example non-linearities on multiple event signals and micro-seismic noise. Non-linearities of the order of 1 percent and less are demonstrated to increase noise levels significantly in certain LP and SP bands.

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TABLE OF CONTENTS

TECHNICAL REPORT SUMMARY

The goal of this research effort is to perform an investigation of the effects of seismometer non-linearities on received signals and to improve understanding of the effects of distortion, caused by seismometers, on later data processing.

Seismometers are designed to convert earth motion into electrical signals. In an ideal seismometer, this conversion would take place without distortion. In an actual seismometer, one must contend with several types of distortion. These distortions affect the type and potential success of all later processing steps. Without proper consideration for the errors committed by the transducer, one can, in fact, come to false conclusions regarding the characteristics of the original signals.

Non-linearities in present seismometers make it difficult to utilize spectral discriminants to solve the "interfering event" problem. The potential advantage of increased bandwidth for improved spectral discrimination is eliminated for non-linear instruments because the problem with non-linearities increases as the bandwidth of the instrument is increased.

A "soft" zero-memory non-linearity is described in Section 2.1 and used to model the non-linear effects of seismometers. Results of application of this non-linearity model to the signal (see 2.2) and noise spectra (see 2.3) demonstrate that non-linearities of the order of 1% can significantly increase noise levels in frequency bands of interest. Also, spurious cross-product terms are generated which could easily be mistaken for low-level events.

For modeled non-linearity levels ranging from 0.1% to 3%, when applied to microseismic noise spectra, resulted in peak spectral noise increases ranging from 1 to 33 db for displacement noise and from 1 to 21 db for acceleration noise. Noise levels in selected long-period and short-period bands increased by as much as 30 db for the 3% distortion level. The example non-linearities are demonstrated to cause significant increases in noise levels for non-linearities of the order of 1% and less. The severity of the problem depends of course on the exact non-linearity levels to be expected in actual seismometers.

Efforts to date have indicated that an expected upper bound on non-linearities is 1%; however, very little information concerning the definition of this distortion level is available. There is a noticeable lack of reliable test data to verify expected levels of non-linearities.

Definition and implementation of non-linearity test procedures are required before reliable bounds can be placed on seismometer non-linearity levels. A preliminary representation is given of desirable features of such test procedures.

1.0 INTRODUCTION

The goal of this research effort is to perform an investigation of the effects of seismometer non-linearities on received signals and to improve the understanding of the effects of distortion, caused by seismometers, on later data processing. This work will also lead to improved methods of combining data from co-located seismometers so as to reduce the effects of these distortions. The availability of modern data processing equipment makes it possible to utilize new approaches to seismometer design and utilization so that distortion effects are minimized.

Non-linearities in present seismometers make it difficult to utilize spectral discriminats to solve the "interfering event" problem. The potential advantage of increased bandwidth for improved spectral discrimination is eliminated for non-linear instruments because the problem with non-linearities increases as the bandwidth of the instrument is increased.

Although it has been generally accepted that analog recording has been a limiting factor in both the broadband and the interfering-event problems, this is most likely not the case. The analog recorder can faithfully record and play back, without need for switching, over a dynamic range of nearly 100 db. The background noise level rises with the signal level, however, so that only about a 30 to 40 db subrange can be utilized in the broadband case. Even with this reduced dynamic range for the recorder, non-linearities of the order of 1% in the seismometer are sufficient to make the seismometer the limiting factor rather than the recorder. This is illustrated in Section 2.0 for the simple case of multiple sinusoidal signals. The effect of non-linearities on the microseismic noise spectrum is also illustrated.

A "soft" zero-memory non-linearity is described and used to model the non-linear effects of seismometers. Results of application of this non-linearity model to the signal and noise spectra demonstrate that non-linearities of the order of 1% can significantly increase noise levels in frequency bands of interest. Also, spurious cross-product terms are generated which could easily be mistaken for low-level events. Thus the relative effects of non-linearities are demonstrated. The next step is to determine acceptable levels of non-linearities for actual seismometers and to recommend methods for verification of these levels.

2.0 TECHNICAL DISCUSSION

2.1 The Problem

Seismometers are designed to convert earth motion into electrical signals. In an ideal seismometer, this conversion would take place without distortion. In an actual seismometer, one must contend with several types of distortion. These distortions affect the type and potential success of all later processing steps. Without proper consideration for the errors committed by the transducer, one can, in fact, come to false conclusions regarding the characteristics of the original signals.

The characteristics of most transducers are similar. The primary design specifications which influence signal distortion are:

- Bandwidth - The effect of instrument bandwidth is to distort the signal by emphasizing certain frequency components at the expense of others.

- Dynamic Range - The dynamic range is the difference between the instrument's self-noise and the maximum signal that can be accepted without exceeding a set level of amplitude distortion. An instrument with inadequate dynamic range will either distort strong signals by clipping them, or mask weak ones with additive noise.

- Linearity - The effect of non-linearities is to distort the relative amplitude of signals. The effect of these non-linearities on signals is not uniquely reversable by later data processing.

Dynamic range can be improved by digitizing the output data at the seismometer. This eliminates noise sources extraneous to the seismometer itself. However, this does not solve the non-linearity problem. In fact, it will be shown that improved dynamic range can make the non-linearity be the limiting source of distortion. Thus, it is desired not only to improve dynamic range but to reduce the effects of non-linearities also.

Non-linearities are a result of such factors as imperfect springs which cause a non-linear compliance, hysteresis or stiction effects which influence damping, and the accuracy of the electromagnetic (or other) pickup. It is theoretically possible to reduce these to almost any desired limit if cost and size are not limiting factors. However, some non-linearity will always exist in seismometers, and should be included in a modeling approach to minimizing distortion in seismic signals.

The effects of non-linearities can be seen in either the time domain or the frequency domain. If the input is a complicated function of time, it can be considered to be equivalent to a Fourier series with many terms. The effect of the non-linearities on the output is to create energy at all sum-and-difference frequencies which existed at the input.

6

Consider, for example, the non-linear response represented by:

$$y = k(\chi - a\chi^3) \quad (1)$$

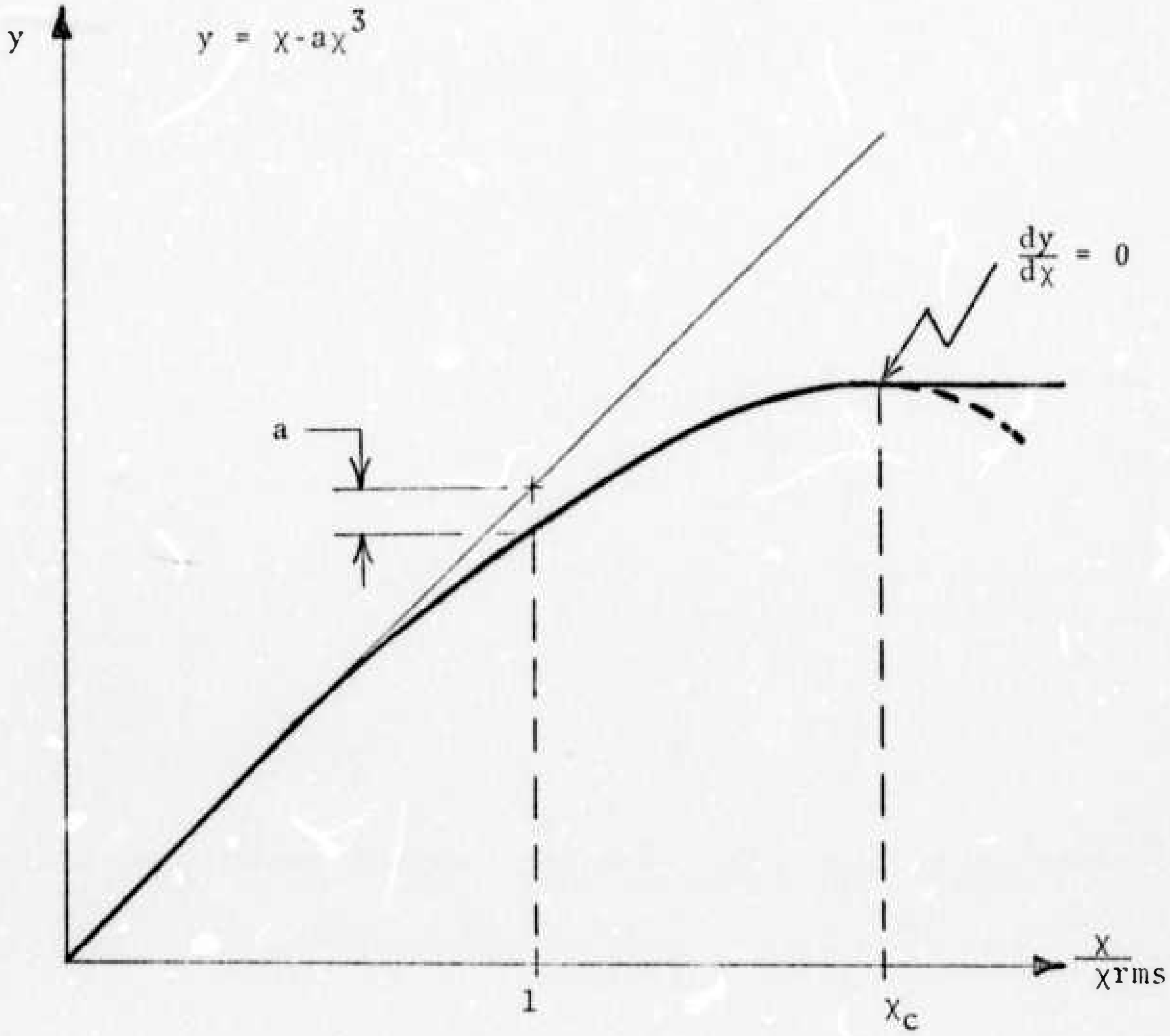
where

χ = the input time function
k = 1
y = the output time function
and a = the distortion for an input of $\chi = 1$

The response curve represented by (1) is shown in Figure 1. In order to relate the distortion to real signals, the response curve is normalized to the input rms value. Thus, a specified distortion level of "a" means that $y = \chi - a$ when χ is at its rms value. The distortion level increases for χ greater than its rms value and decreases to zero as χ goes to zero.

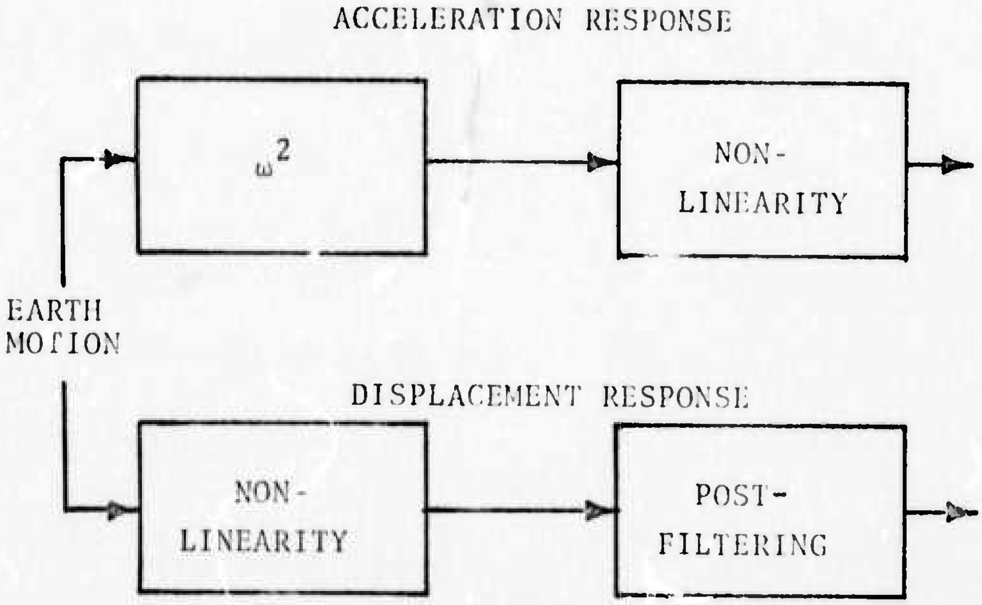
Because of the nature of the non-linearity model, the transfer function goes to zero slope, then negative, as the cubic term predominates. As a safeguard against the negative slope, a clipping level is defined where the slope goes to zero. This level is a function of the value of "a" and is given in Figure 1 for example values of "a" from 0.1% to 3%.

The expected non-linear response and its point of action are not well understood. Figure 2a illustrates two examples of how the non-linearity might react with earth motion. In the top part of the figure the non-linearity acts on earth acceleration. In the bottom part of the figure the non-linearity acts on earth displacement. Other questions concerning the

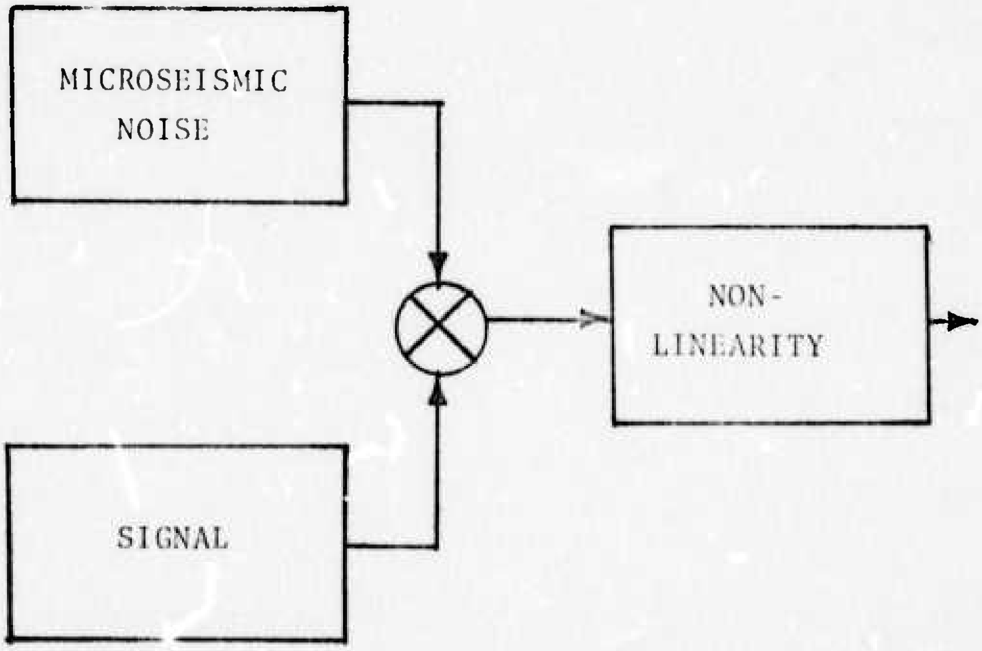


a	χ
0.001	18.25
0.003	10.54
0.01	5.78
0.03	3.33

Figure 1: Symmetric, Zero-Memory Non-Linearity



a) NON-LINEARITY POINT OF ACTION



b) ANALYSIS MODEL

9

Figure 2: Non-Linearity Analysis

point of action include whether the non-linearity is mechanical (springs, etc.) transducer-related (moving coil pick-off, capacitor measurement, etc.) or electronics related.

For the analysis model shown in Figure 2b used in this program, input and output spectra were compared for three cases: 1) multiple sinusoid, 2) displacement microseismic noise, and 3) acceleration microseismic noise. Results of the application of the non-linearity model in Figure 1 to these three cases are discussed in the remainder of this section.

2.2 Sine Wave Inputs

Signals consisting of equally weighted sinusoids were generated and processed through the non-linearity. The input spectrum for a signal consisting of two sinusoids at frequencies f_1 and f_2 is shown in Figure 3. As illustrated in the output spectrum (see Figure 3) for this case, cross-product terms are generated by the non-linearity which have amplitudes about 40 to 50 db below the true signal components. The value of "a" in this case was 1%.

Several conclusions can be drawn from this example:

1. The distortion added by even a good seismometer can be appreciable when viewed in the frequency domain. Since this is the case, recorders which have specified dynamic ranges of 30 to 40 db are adequate to record the data generated through these seismometers.

10

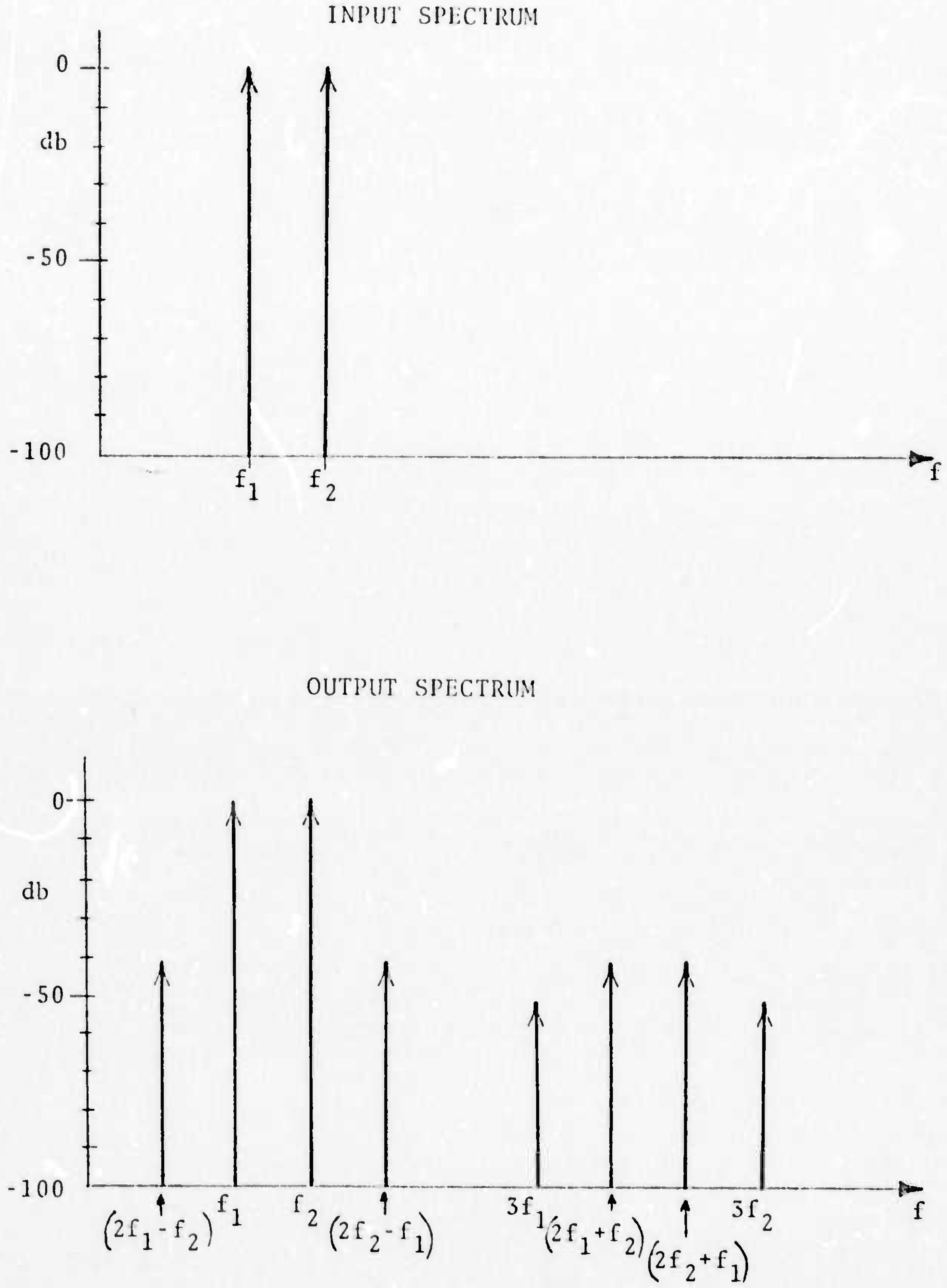


Figure 3: Effect of Example One-Percent Non-Linearity on Sine Wave Input Signals.

2. The generated spectrum is complex for this simple case. It would be difficult to remove the non-linear effects, especially if mixed in with other effects such as linear filtering.

3. The added components occur over a much wider frequency band than is occupied by the original signal.

4. One would suspect low-level signals in the presence of strong peaks as being spurious.

2.3 Non-Linearity Effects on Microseismic Noise

A model for microseismic noise (DISPLACEMENT MODEL 3) covering the period range from 0.1 to greater than 100 seconds was synthesized using measurement data from various sources [1] [2] [3]. An alternate model (DISPLACEMENT MODEL 4) based on more detailed measurement for long period noise including the peak at 18 seconds was also developed [4]. These two displacement noise spectra are shown in Figure 4. A program was devised for generating a noise time signal which exhibits the spectral properties shown in Figure 4 and covering the range from .002 Hz to 8 Hz (.125 to 500 seconds period). These noise time signals were then processed through the non-linearity and comparisons were made between input and output spectra.

Estimates for the corresponding acceleration spectra were obtained by doubly differentiating with respect to time the displacement curves. Results of this process are shown in Figure 5 for noise models 3 and 4.

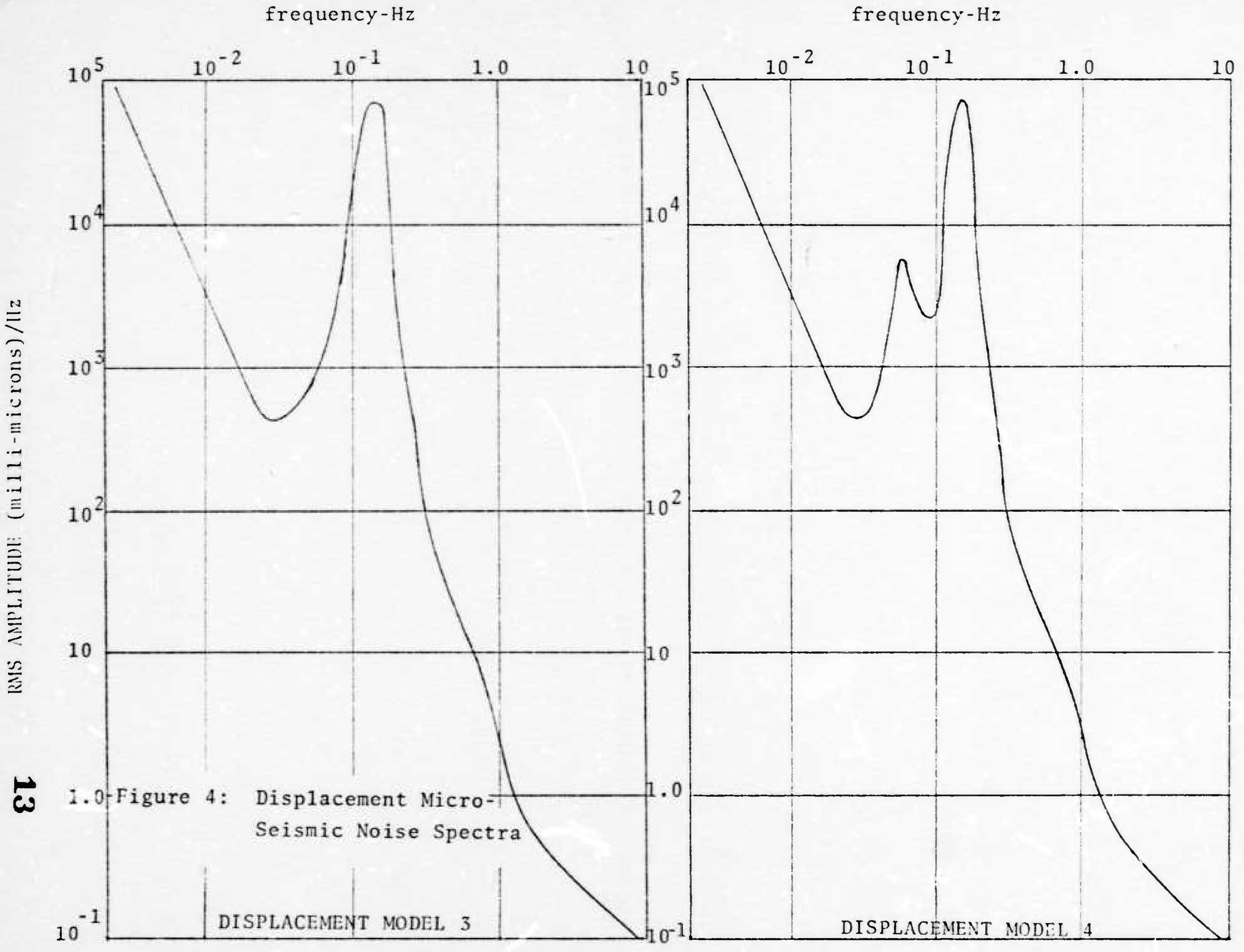


Figure 4: Displacement Micro-Seismic Noise Spectra

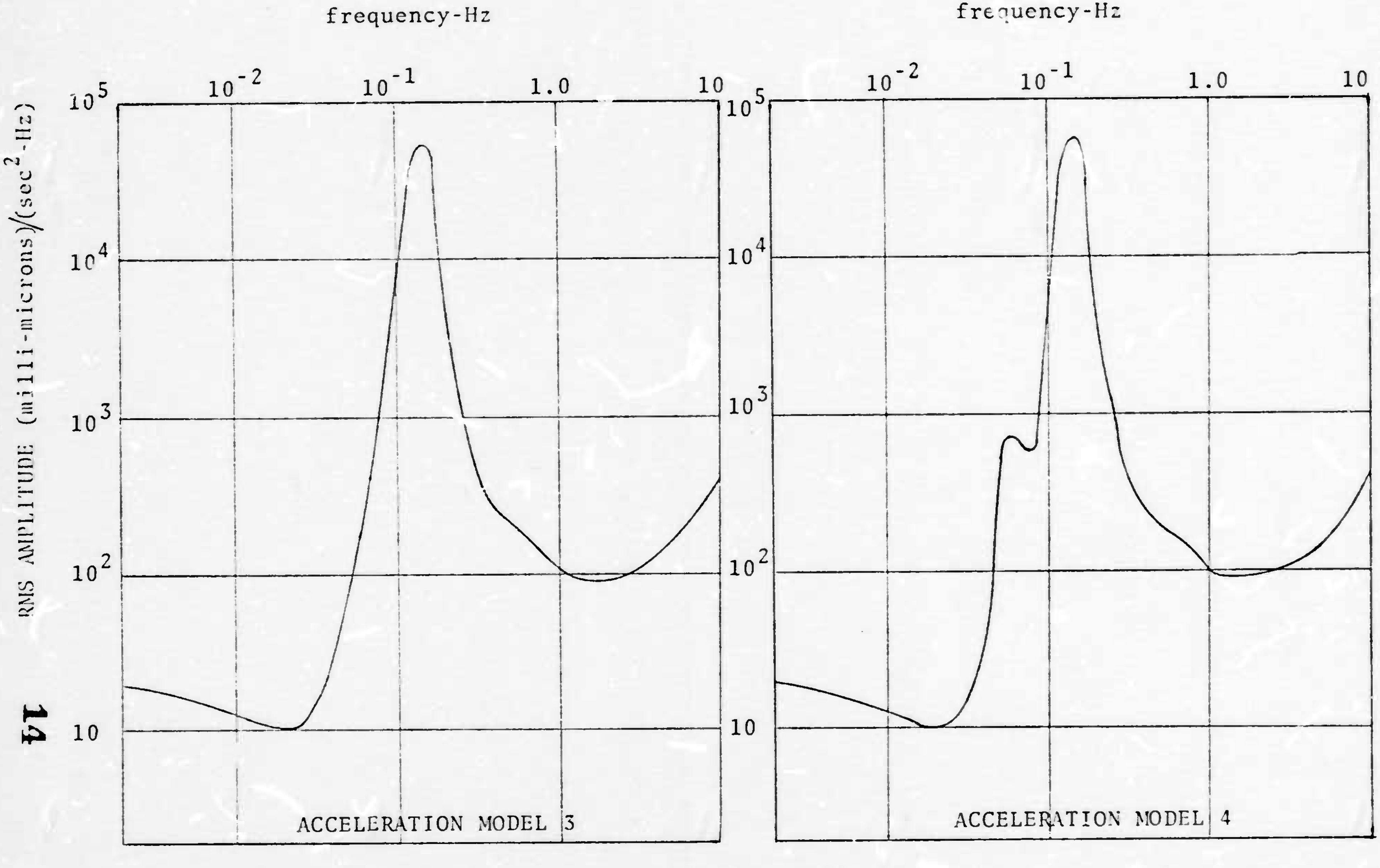


Figure 5: Acceleration Micro-Seismic Noise Spectra

Results of application of the non-linearity model to displacement noise are shown in Figure 6 for the two noise models. Input spectra are shown as solid lines and output spectra are shown for values of distortion (at rms) of 0.1%, 0.3%, 1.0% and 3%. As would be expected the high energy microseismic peak at approximately 6-seconds when passed thru the non-linearity model causes significant increases in noise energy at the third harmonic level (approximately 0.4 Hz) and at the low (difference) frequencies. A significant increase in a portion of the 20-40 second band is observed. Peak differences as high as 33 db at 0.4 Hz are observed with peak differences in the LP band at approximately 12 db.

The results of Figure 6 indicate the expected output spectra for a non-linearity acting on the earth displacement if the input spectra are truly representative of earth displacement noise. It is emphasized that these input spectra are based on measurement data and are in fact seismometer output spectra upon which non-linearities (if present) have already acted.

Figure 7 shows results of the non-linearity model acting on the acceleration microseismic noise. Results are similar for both models 3 and 4, the major difference being the notch at 18 seconds for model 4. The result of the non-linearity is to fill in this notch and for both models is to increase energy in the low frequencies and near the third harmonic. The increase in low frequency energy for the acceleration model is more pronounced because of the relative levels of low and high frequency energy at the input. That is, for the acceleration noise model, significant energy in the range from 1 to 8 Hz is also pumped down into the LP band.

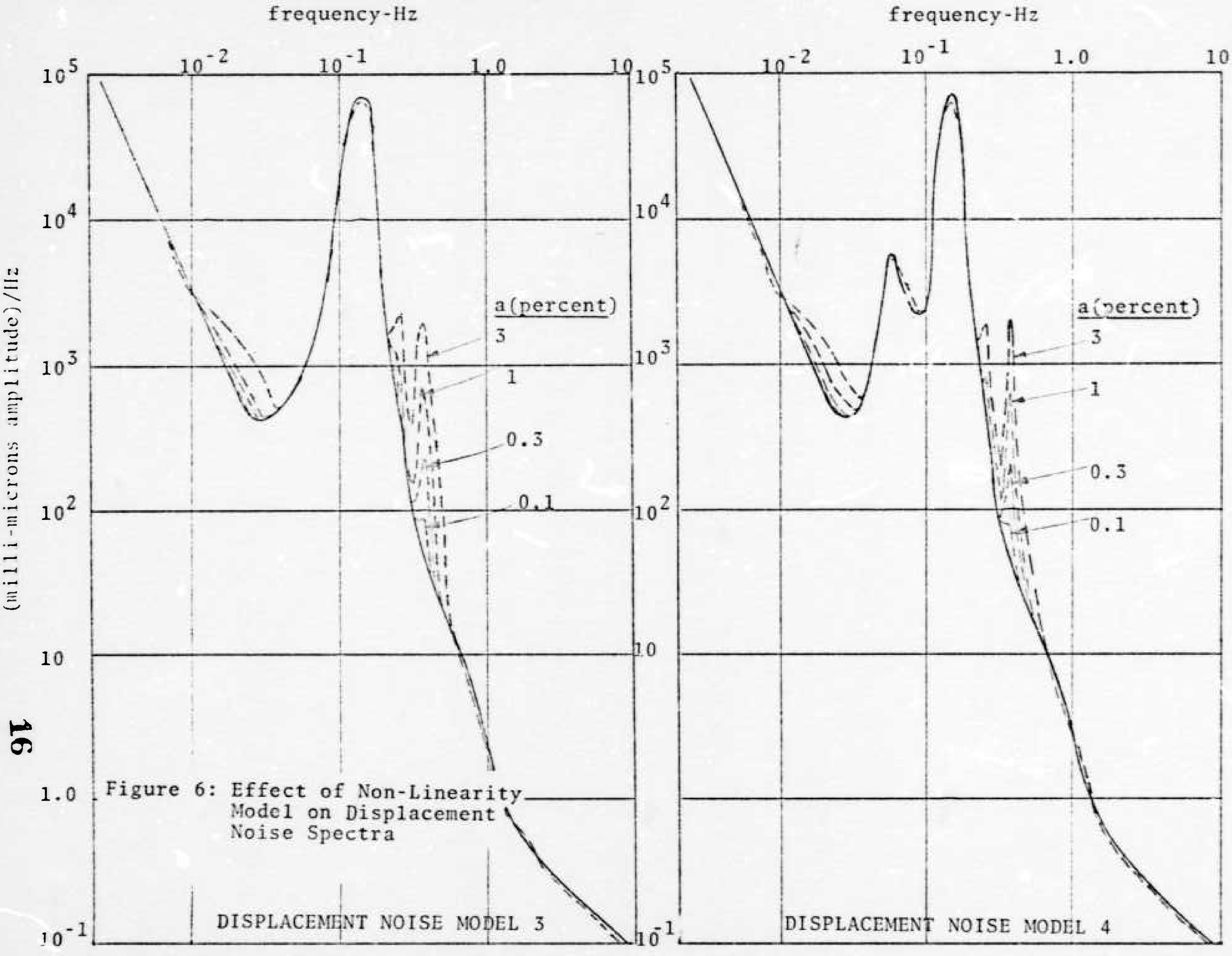


Figure 6: Effect of Non-Linearity Model on Displacement Noise Spectra

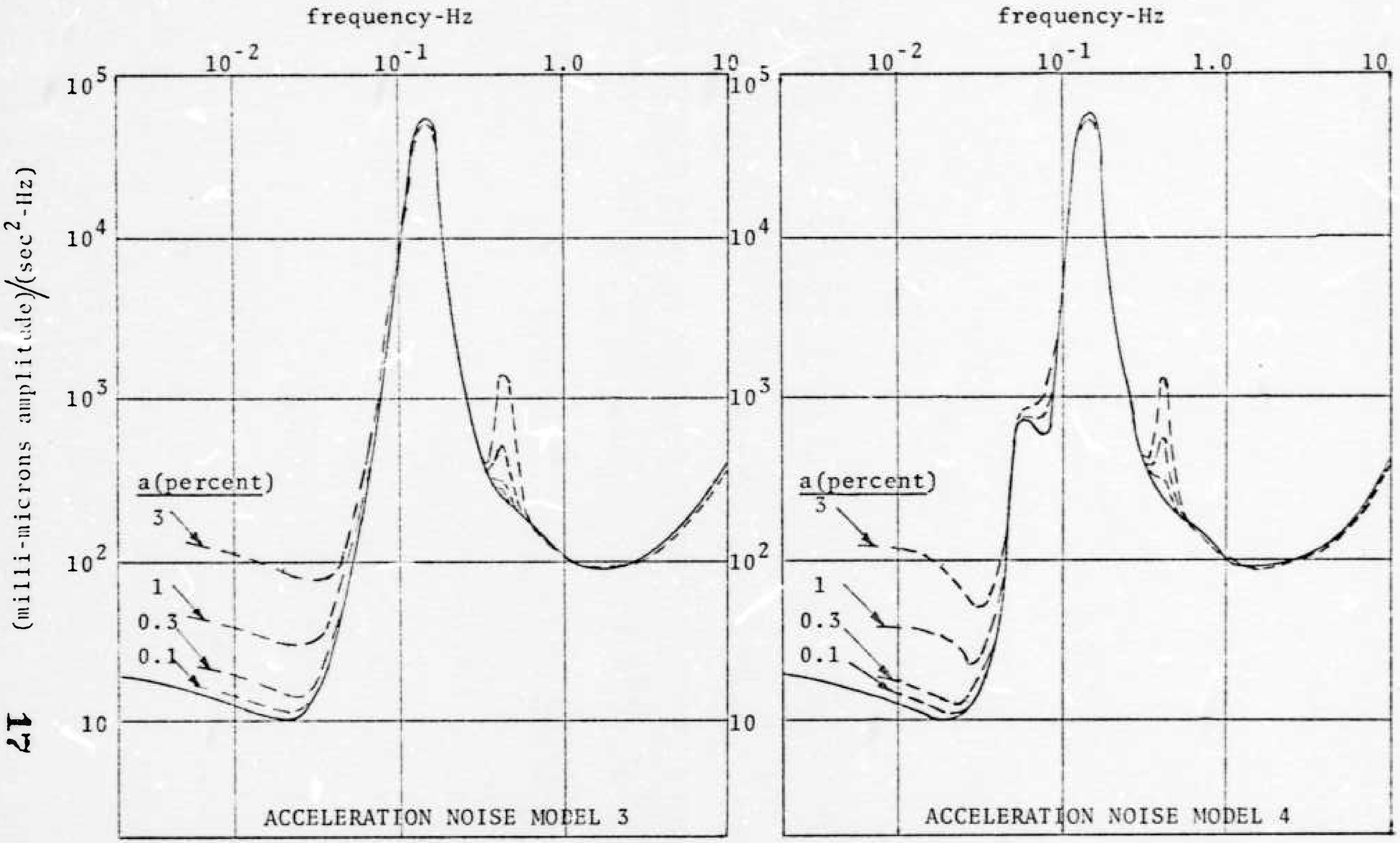


Figure 7: Effect of Non-Linearity Model on Acceleration Noise Spectra

Peak spectral noise increase occurs in the LP band and ranges from about 1 db for a = 0.1% to about 21 db for a = 3%. Thus, for an instrument with non-linearities acting on the acceleration input to the instrument, the non-linearity levels examined would cause significant degradation of the system performance.

Figures 6 and 7 demonstrated relative spectral noise increases due to the described non-linearities. Of concern also is the relative total noise increase in finite SP and LP bands of interest. A spectral integration scheme was employed to compute relative input and output power in representative long-period and short-period bands. Results of this computation for displacement and acceleration noise models 3 and 4 are given in Figure 8.

Because of the sharp slopes of the noise curves and the logarithmic frequency scale, energy in the selected SP and LP bands is very sensitive to the exact bandpass limits, and results of the bandpass integration in some cases may not appear to agree with Figures 6 and 7. The point to be made by Figure 8 is that gross differences in bandpass noise levels are observed for non-linearities of the order of 1% and thus reduce the effective signal-to-noise performance of the system. This degradation of signal-to-noise ratio can seriously impair the ability to detect low-level events in the given LP and SP bands.

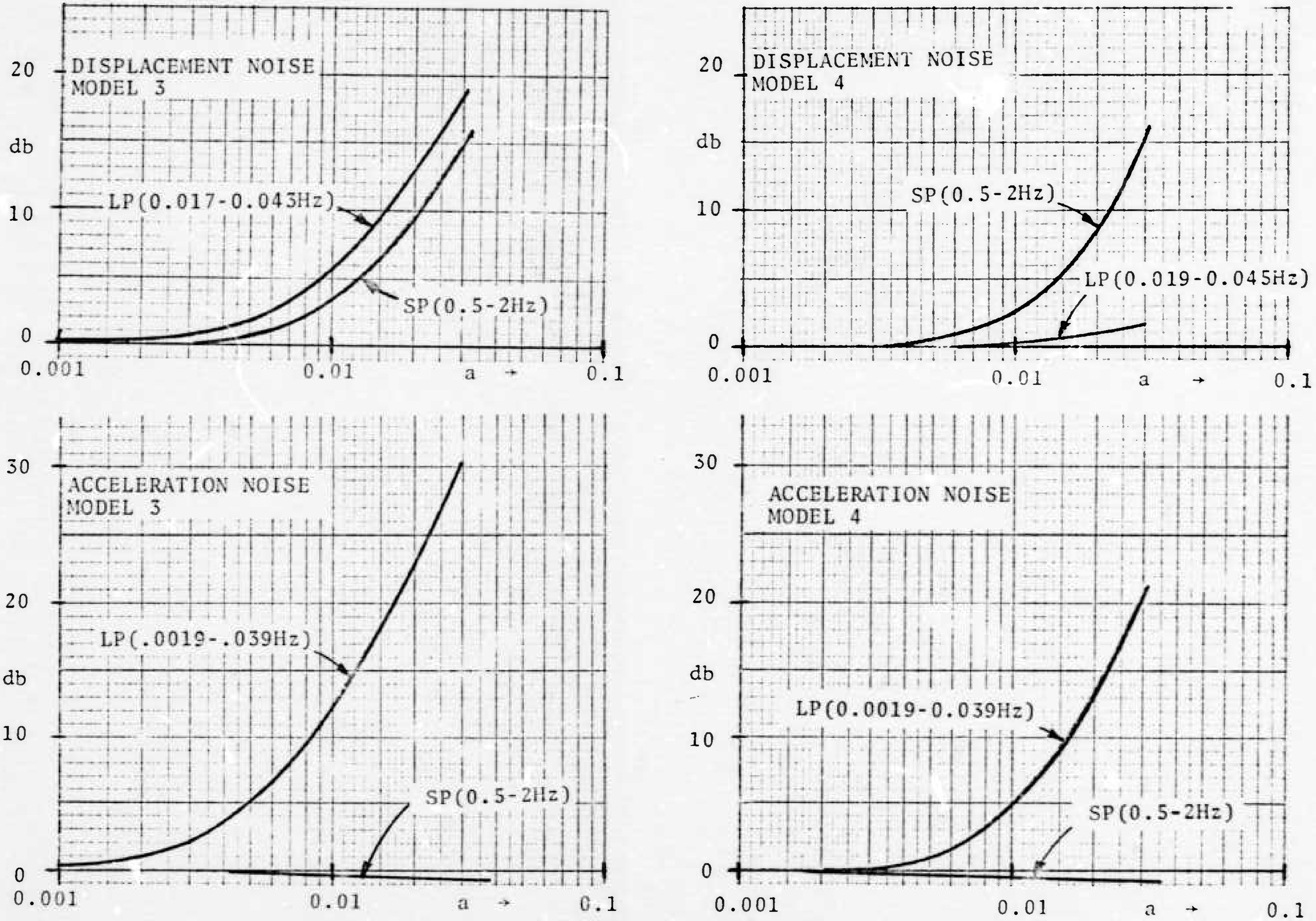


Figure 8: Increase in LP and SP Bandpass Noise because of Non-Linearity

3.0 CONCLUSIONS AND COMMENTS

It has been demonstrated that a wideband seismometer exhibiting the example non-linearity would produce an output spectrum which could seriously degrade overall performance. For the interfering event case there would be confusion in trying to separate low-level events from cross-product terms of larger events.

For the case of low signal-to-noise it is demonstrated that in certain spectral bands, the example non-linearities increase noise levels sufficiently to completely mask low-level events. The severity of the problem depends of course on the exact non-linearity levels to be expected in actual seismometers. Efforts to date have indicated that an expected upper bound on non-linearities is 1%; however, very little information concerning the definition of this distortion level is available. There is a noticeable lack of reliable test data to verify expected levels of non-linearities.

Definition and implementation of non-linearity test procedures are required before reliable bounds can be placed on seismometer non-linearity levels. Figure 9 is a preliminary representation of desirable features of such tests. The idea is to compare broadband instrument results with those from "standard" SP and LP instruments.

A major task in implementing the ideas represented in Figure 9 is the definition of "standard" seismometers. Ideally they would be linear; however, it might be sufficient that they respond only to specific passbands such that out-of-band energy is in no way coupled into the passband.

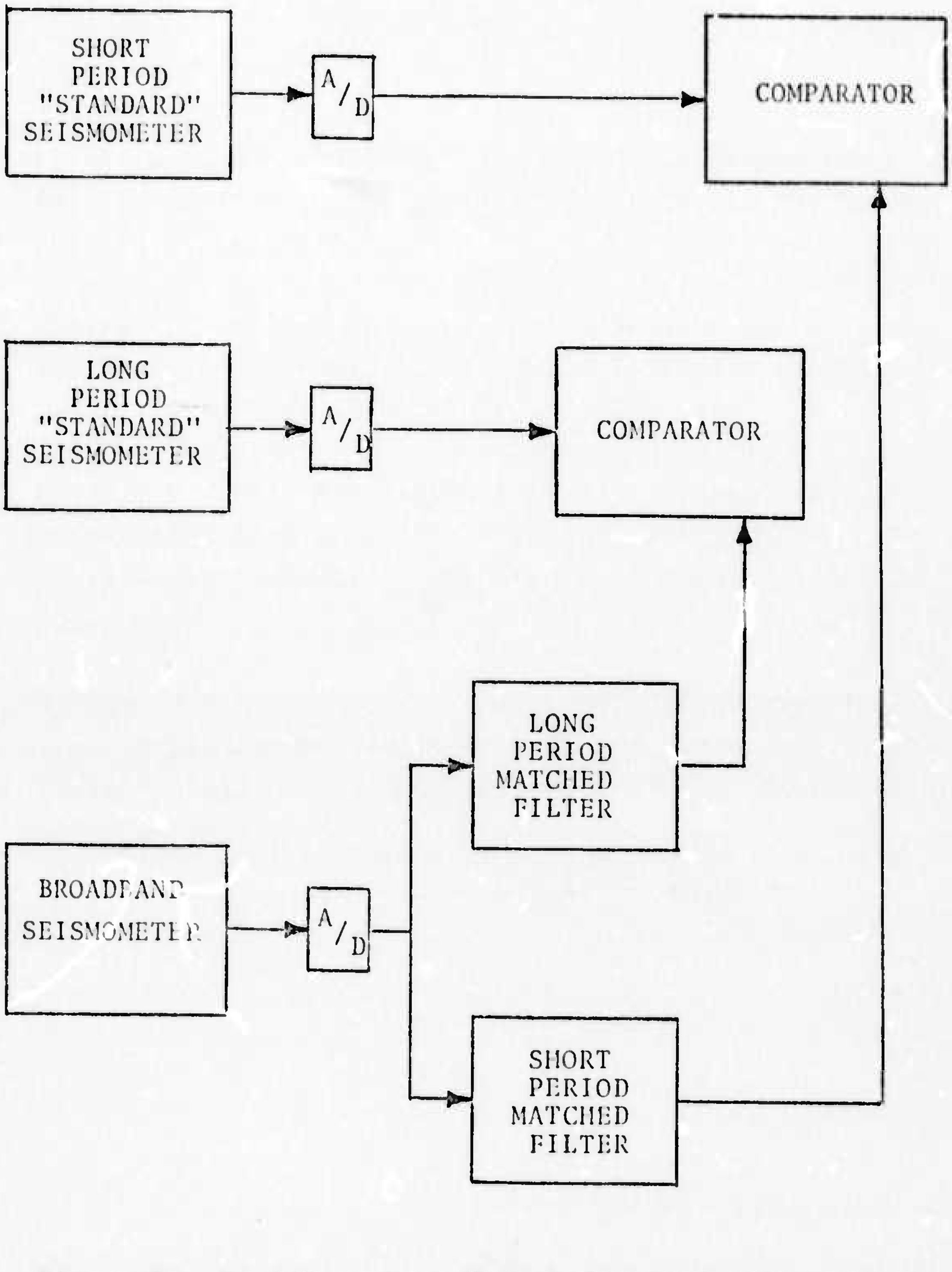


Figure 9: Candidate Test Method for Evaluating Relative Non-Linearities.

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