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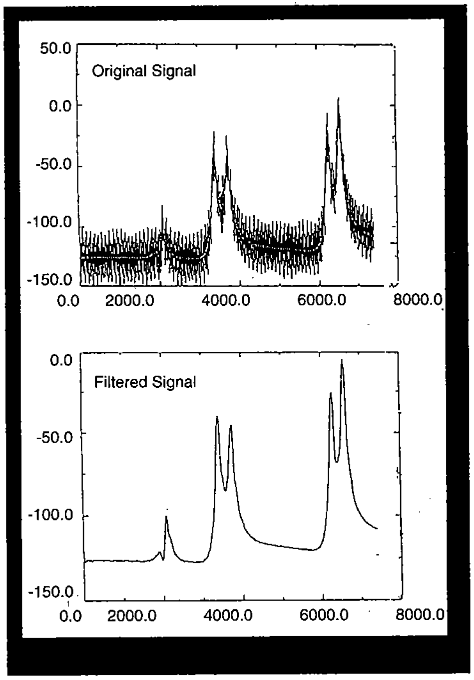

Digital Signal Processing For Mn/ROAD Offline Data

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A computer program based on statistics and signal process theory was developed to automatically detect peaks and valleys from sensor response signals obtained during live heavy truck and falling-weight deflectometer testing. Statistics are applied to each signal to characterize the nature of the reponse signal and to make the detection of maxima and minima more efficient. Noise effects are treated by applying filtering techniques including Fast Fourier Transform and time domain filtering.

The Procedure was found to work effectively and is now being used to process pavement response data that has been collected at the Minnesota Road Research Project (Mn/ROAD) over the past three years. The output file from the program is readily loaded into the Mn/ROAD database.

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Digital Signal Processing for Mn/ROAD Offline Data

Final Report

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TABLE OF CONTENTS

List of Figures

EXECUTIVE SUMMARY

The primary concern in pavement engineering and design is the ability to accurately evaluate pavements and estimate pavement performance under traffic loads. Knowledge on how a pavement responds to actual truck traffic is essential for the development of mechanistic design methods and for validating pavement performance models. A key feature of the Minnesota Road Research Project is the in situ pavement response sensors. These sensors allow researchers to study the response of pavement structures under different loads.

At the Minnesota Road Research Project (M/nRoad), a full-scale pavement test facility constructed by the Minnesota Department of Transportation (Mn/DOT), pavement response testing using both truck and falling-weight deflectometer loads has been ongoing for several years. The data from these tests consists of time-history traces from the various sensors. Typically, the engineer is concerned with the maximum or minimum response underneath a truck tire or falling-weight deflectometer plate. In order to extract the required information from the sensor time-histories an accurate, efficient method of analysis was needed.

In this study, a computer program based on statistics and signal process theory was developed to automatically detect peaks and valleys from sensor response signals obtained during live heavy truck and falling-weight deflectometer testing. Statistics are applied to each signal to characterize the nature of the response signal and to make the detection of maxima and minima more efficient. Noise effects are treated by applying filtering techniques including Fast Fourier Transform and time domain filtering.

The procedure was found to work effectively and is now being used to process pavement response data that has been collected at Mn/ROAD over the past three years. The output file from the program is readily loaded into the Mn/ROAD database.

CHAPTER 1

INTRODUCTION

A primary concern in pavement engineering and design is the ability to accurately evaluate pavements and estimate pavement performance under traffic loads. Accurate knowledge on how a pavement responds to actual truck traffic is essential for the development of mechanistic design methods and for validating pavement performance models. A key feature of the Minnesota Road Research Project is the in situ pavement response sensors. These sensors allow researchers to study the response of pavement structures under different loads.

At the Minnesota Road Research Project, a full-scale pavement test facility constructed by the Minnesota Department of Transportation, pavement response testing using both truck and falling-weight deflectometer loads has been ongoing for several years. The data from these tests consists of time-history traces from the various sensors. When a truck passes over a buried sensor the signal contains multiple peaks; each peak corresponds to the passage of an individual axle. Typically, the engineer is concerned with the maximum or minimum response underneath a truck tire or falling-weight deflectometer plate. In order to extract the required information from the sensor time-histories an accurate, efficient method of analysis was needed.

During construction of the facility every effort was maintained to minimize noise effects on each type of sensor system, including shielded cables and twisted-pair conductors. However, because the sensors are exposed to a noisy environment, the signals from the various sensors can become corrupted, which means the measurements can contain the effects of noise. Interpretation of data from affected signals can lead to inaccurate or even false results. Thus, it is necessary to treat noise effects on the measurements during the analysis procedure.

In this study, a computer program based on statistical methods and signal process theory was developed to automatically detect peaks and valleys from sensor response signals obtained during live heavy truck and falling-weight deflectometer testing. Statistical methods are applied to each signal to characterize the nature of the response signal and to make the detection of maxima and minima more efficient. Noise effects are treated by applying filtering techniques including Fast Fourier Transform and time domain filtering. The procedure was found to work effectively and is now being used to process pavement response data that has been collected at Mn/ROAD over the past three years. The output file from the program is readily loaded into the Mn/ROAD database.

CHAPTER 2

FOURIER TRANSFORM AND TIME DOMAIN FILTER

Theory

If a time series is given by function $y(t)$, in order to see the frequency distribution of $y(t)$, an integral can be applied to $y(t)$. The integral is defined as

$$Y(f) = \int_{-\infty}^{\infty} y(t)\, e^{2\pi i f t} dt$$

where t is time and f is frequency. It simply means that a time domain function $y(t)$ can be transferred into a quantity $Y(f)$ as a function of frequency (f) in a frequency domain. Consequently, the function $Y(f)$ can be inversely transferred back to the time domain by

$$y(t) = \int_{-\infty}^{\infty} Y(f)\, e^{-2\pi i f t} df$$

It can be viewed that functions $y(t)$ and $Y(f)$ are the two different representations of the same function. One goes back and forth between these two representations. This process is called Fourier Transform.

However, a finite number of sampled points is always obtained from an actual experiment so a discrete Fourier Transform is needed for a practical application and programming. The discrete Fourier Transforms are approximations of the above integrals in discrete summation forms, which are given below

$$Y(f_j) = dt \sum_{k=0}^{N-1} y_k e^{2\pi ikj/N} \qquad (frequency\ domain)$$

$$y_k = \frac{1}{N} \sum_{j=0}^{N-1} Y_j e^{-2\pi ikj/N} \qquad (time\ domain)$$

where *N* is the total number of samples and *dt* is the sampling interval. Normally, an effective computational algorithm is used to calculate above summations. Therefore, the transform is referred to as Fast Fourier Transform (FFT) [1].

As mentioned above, the measured signal could contain environmental noise effects which usually have high frequencies but could also be contaminated by 60 Hz interference. A convenient and effective way to remove the noise effects is to take the whole data record y(t), perform a FFT, filter certain frequencies from noise (for example 60 Hz noise), then perform the inverse FFT to obtain a filtered data set in time domain.

However, the elimination of certain frequencies can cause a natural damped "ring" in the signal after the inverse FFT. This is because the effect of the filter is actually to eliminate some terms in the Fourier series which are in the form of sine and cosine. To minimize this mathematic damping, a time domain filter was found to work well for Mn/ROAD data [2]. The filter is given by

$$z_n = x_n - r_n$$

where x_n is the original sample data after the inverse of FFT; r_n is defined as

$$r_n=b_1x_n+b_2x_{n-1}+b_3x_{n-2}-a_2r_{n-1}-a_3r_{n-2}\ (n>2)$$

where $b_1=b_3=g^2/g_1$, $b_2=2g^2/g_1$, $a_2=g/g_1$ and $a_3=g_3/g$.

The initial values can be calculated from

$$r_1=(b_1+b_2+b_3-a_2-a_3)\,x_1$$

$$r_2=b_1x_2+(b_2+b_3-a_3)\,x_1-a_2y_1$$

The coefficients are as follows:

$$g=\tan(\pi f_c s)$$

where f_c is the cut-off frequency and s is sampling interval.

$$g_1=1+1.2g+g^2$$

$$g_2=2g^2-2$$

$$g_3=1-1.2g+g^2$$

A phase switch was observed when filtering data using this filter. However, the phase switch can be eliminated through applying this filter once more from the end of the filtered signal to the beginning of the signal (reverse order).

Results

The frequency analysis (Fig. 1) shows a relatively large amplitude at around the 60 Hz in frequency domain. Fig. 2 shows a concrete strain sensor measurement which is severely contaminated by noise. To minimize the noise effects on the signal and enhance the signal of measurements, the band-pass filter was first applied to the signal to eliminate the high frequency noise. Notice that a restriction on the FFT is that the number of samples must be an integer power of 2. However, the number of samples from our experiments does not follow this form. So, an artificial extension of the data points was made prior to applying FFT. The values of extension points are taken to be the average of the last 100 points of the signal. Then, the time domain filter was used to reduce the ring effect. The filtered signal is presented in Fig. 3. Fig. 4 gives the superposition of an original and filtered signal for a FWD test. More examples from truck tests are showed in Fig. 5. Furthermore, for a less corrupted signal (Fig. 6), the filtering process also appears to work very well (Fig. 7).

CHAPTER 3

PROCEDURES OF AUTOMATIC PEAK DETECTION PROGRAM

Program for Truck Tests

As mentioned above, when a truck passes over a sensor area, the signal from a sensor response contains multiple peaks. Fig. 5 shows the typical responses of strain sensors embedded at the bottom of pavements to the Mn/ROAD truck which is a 5 axle rig. The signal clearly has five peaks, each one corresponds to the pass of each axle of the truck. It also can be seen in Fig. 5 that the signal from a strain sensor could have two types of response: (a) tensile and (b) compressive responses. The upwards response represents tensile strain at the bottom of pavement. However, if the truck is far away from a strain sensor, the signal from the sensor could show a downwards response, which means that compressive strain has occurred at the bottom of pavement.

In order to automatically detect the peaks using a computer program, a criterion has been developed to distinguish between these two types of responses. This is because the algorithms in the computer program for finding peak values for the two cases are different. For the tensile response, the program searches for local maximum values, which are the individual peaks appearing in the maximum value form. Otherwise, the program looks for local minimum values, which are the individual peaks appearing in the minimum value form for the downwards response case. The criterion used in the program is as follows: (1) find the global maximum (*gmaxp*) and minimum (*gminp*) values from the signal being analyzed; (2) calculate the average value of the signal (*avg*); (3) if (*gmaxp*+*gminp*)/2 is greater than the average value, then the program searches for the peak values for the upwards response case (refers to case 1), otherwise it looks for peaks for the downwards response case (refers to case 2). After the program has determined which case the signal belongs to, the program follows the following procedures to find the peaks.

For case 1, a trigger level is set above the base line level by

`TRIG=avg+abs(a1-avg)/3`

where *avg* is the average value of the signal being analyzed and *a1*=(*gmaxp*+*gminp*)/2. Once the trigger level is given, the program checks if the value of each point of the signal is greater than *TRIG*. If the value at a point is larger than *TRIG*, then a window with a certain size (in terms of number of samples) is chosen starting from that point. The program then steps through the following procedures. The maximum value in each window is found by the program, but obviously not all maximum points are the peak points which correspond to the truck axles. If the size of the window is appropriately selected, then a window should only contain one peak corresponding to an axle of the truck. The criterion used to select a window size is that there should not be two peaks corresponding to the truck axles within the window. The size of the window depends on the truck speed and sampling rate and can be estimated. For example, if the truck speed is 128 kph (80 mph) and the sampling rate is 2000 Hz, for the Mn/ROAD truck with 1.194 meters (47 inches) distance between the two closest axles, the number of data points between two consecutive peaks are about 66. So, a window size of 50 points is used in the program to ensure that no two peaks corresponding to the truck axles are contained within one window.

In order to find the peaks from the maximum values from each window, the following procedures have been developed: (1) select 40 points before and after the selected maximum point within each window, then perform linear regression on these two segments; if the two slopes change sign, then this maximum point is selected as a "candidate" for a peak since the slope of the tangent at the peak point should be zero; (2) find maximum values of the 40 point sample which are before and after the selected peak candidate, then check if the value of the peak candidate is greater than the maximum values from each 40 points. If it is, then the candidate is selected as a peak, otherwise, the candidate is rejected and the program proceeds to the next window to repeat analysis. This process is continued until the end of the signal. In such a way, all the peak values corresponding to the truck axles are determined.

For case 2, the trigger level is set by

$$TRIG = avg-abs(a1-avg)/3$$

The procedures for finding the peaks are the same as the procedures described in case 1, except that the program searches for minimum values, instead of searching maximum values.

The program calculates the mean (*M*) and standard deviation (*SD*) of the first 200 points before and after the filtering. The mean value after the filtering is used as the base-line value (reference value). The relative peak value which is the difference between absolute peak value and the reference value is stored in an output file. Furthermore, the following criteria have been found normally to work well for detecting a noisy or unresponsive channel: if a channel is a noisy channel, then its maximum (*gmaxp*) and minimum values (*gminp*) are normally satisfy the condition

$$gmaxp < M+6*SD \text{ and } gminp > M-6*SD$$

If the program detects such a signal satisfying this condition, the program recognizes it as a noisy channel and places a notice in the output file for the channel. This criterion is used in the program before and after the filtering to more effectively detect a noisy channel. Moreover, if a sensor is totally unresponsive or a channel does not connect to any sensor, the signal is a flat horizontal line or all the values of the signal are zero. In such a case, the standard deviation of the signal is zero. So, if the program finds such a channel, a notice is also stored in the output file for the corresponding channel.

In summary, the following presents a brief logic of the procedures for the peak detection program:

Step 1: Detect noisy or unresponsive channels. If a channel is not a noisy or unresponsive channel, then

Step 2: Apply FFT to eliminate some high frequency noises.

Step 3: Apply the time domain filter twice (forwards and backwards) to minimize the mathematical damping.

Step 4: Reevaluate the channel for unacceptable noise levels or no response. If a channel is determined to be acceptable then

Step 5: Follow the peak detection procedures described above to find peak values.

Program for FWD Tests

Another program has been developed specially for the FWD tests. As we know, a signal from a sensor response under the FWD test should ideally contain one peak which corresponds to one FWD drop. A typical sensor response to a FWD load is shown in Fig. 8. The procedures for finding the peak are the same as those for truck test, except that only one peak is picked by the program, instead of searching multiple peaks. However, a feature of signals from FWD tests is that the base-line value shows a slight drop just prior to the peak (Fig. 8). This is due to the release of the FWD weights from the catch. Because the weights of the FWD are in free fall, the base-line value shows a small drop just before the peak. So, the reference value should be taken as the mean of this portion of the response. This feature is considered in the peak pick program designed for FWD tests.

CHAPTER 4

SUMMARY

A procedure based on statistics and signal process theory was developed to automatically detect peaks and valleys from pavement response sensor signals obtained during live heavy truck and falling-weight deflectometer testing. The procedure is embodied in a series of computer programs that provide a quick, efficient way of analyzing data that would be impossible to do manually.

Several features contribute to the general applicability and stability of the procedure. Statistics are applied to each signal to characterize the nature of the response signal and to make the detection of maxima and minima more efficient. The program also detects unresponsive channels so that minimal processing time is spent on them. Noise effects are treated by applying filtering techniques including Fast Fourier Transform and time domain filtering. The procedure was found to work effectively and is now being used to process pavement response data that has been collected at Mn/ROAD over the past three years. The output file from the program is readily loaded into the Mn/ROAD database.

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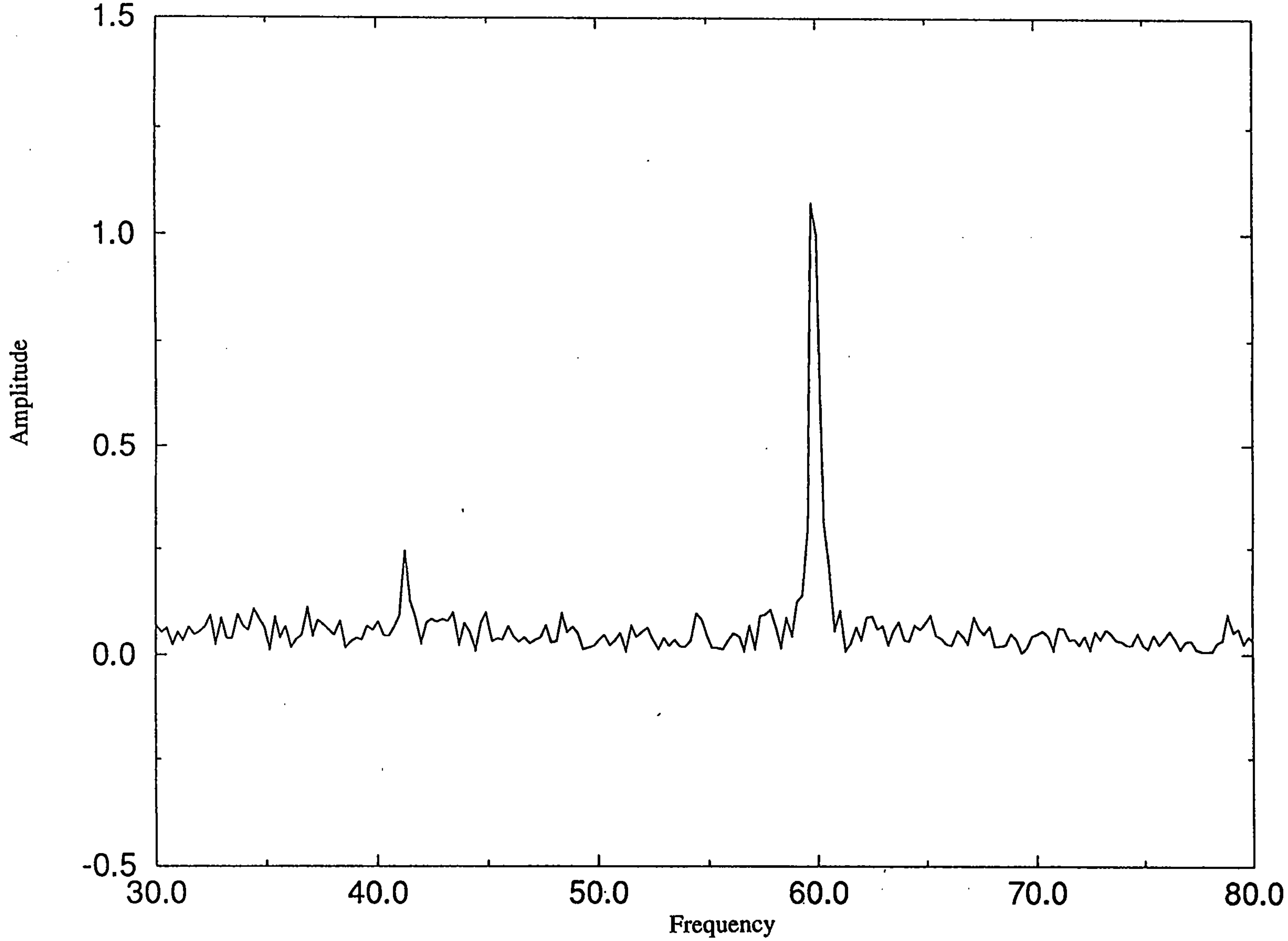


Figure 1. A typical frequency distribution.

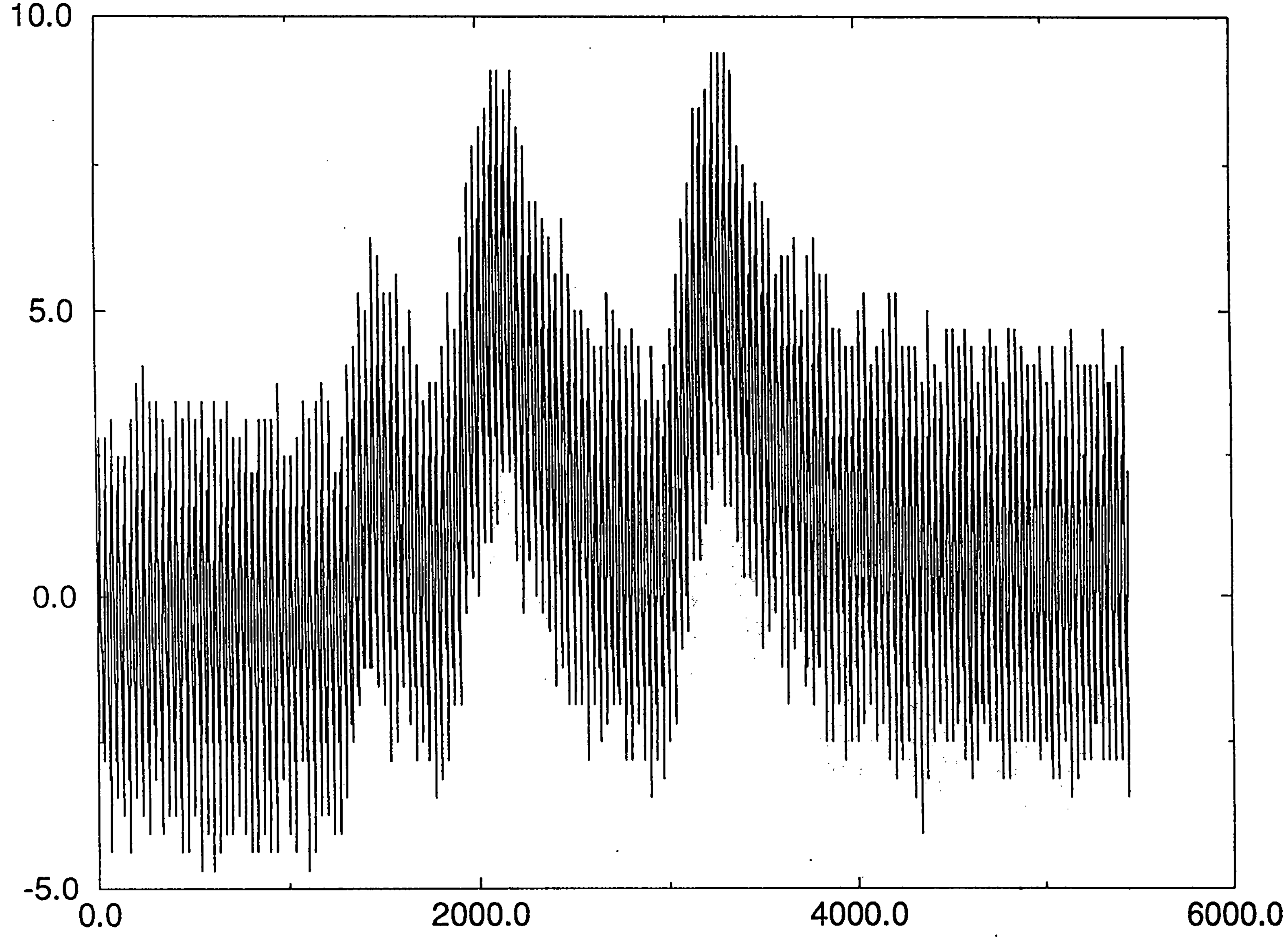


Figure 2. An original signal contaminated by noises

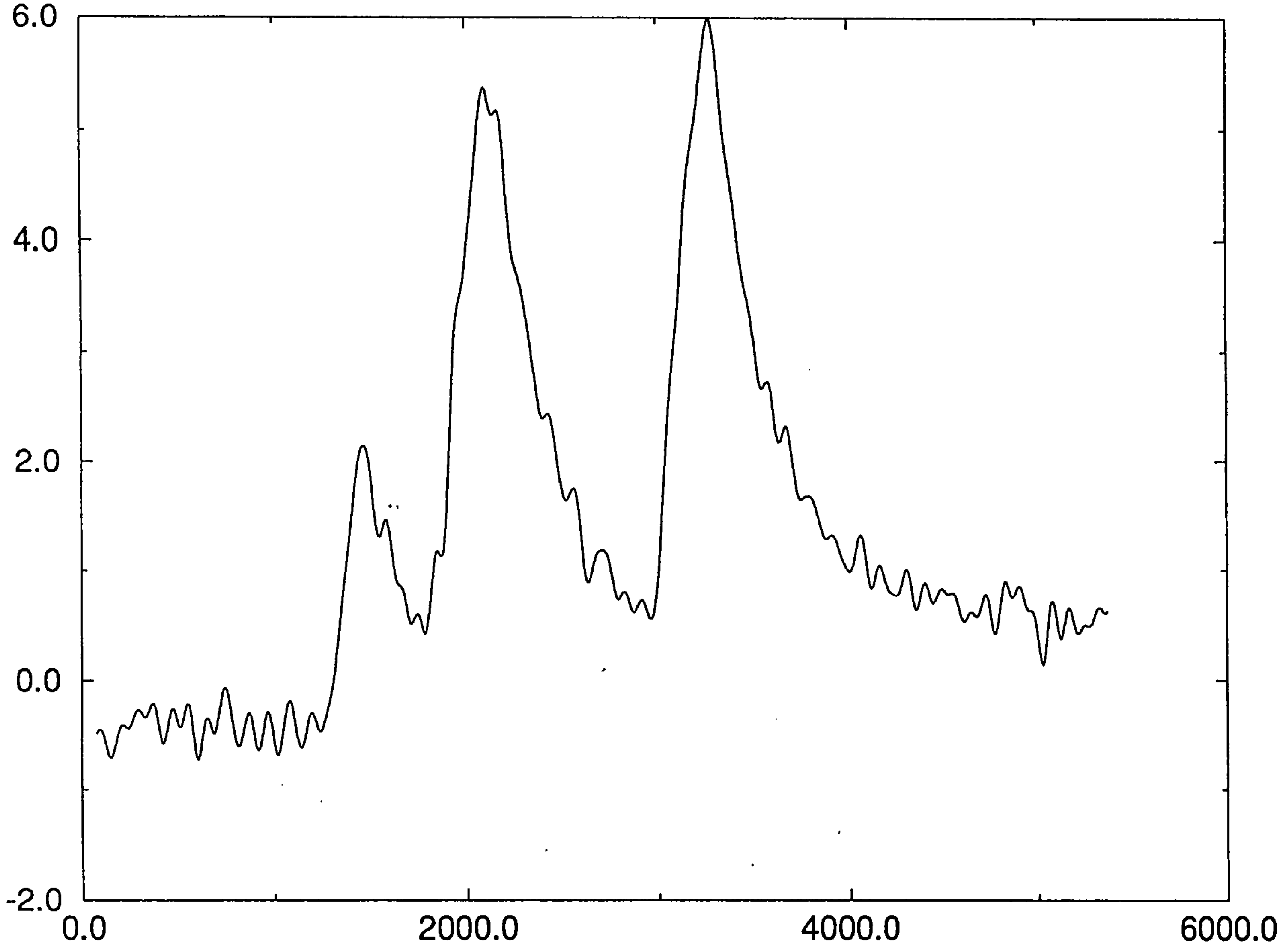


Figure 3. The filtered signal of the signal shown in Figure 2.

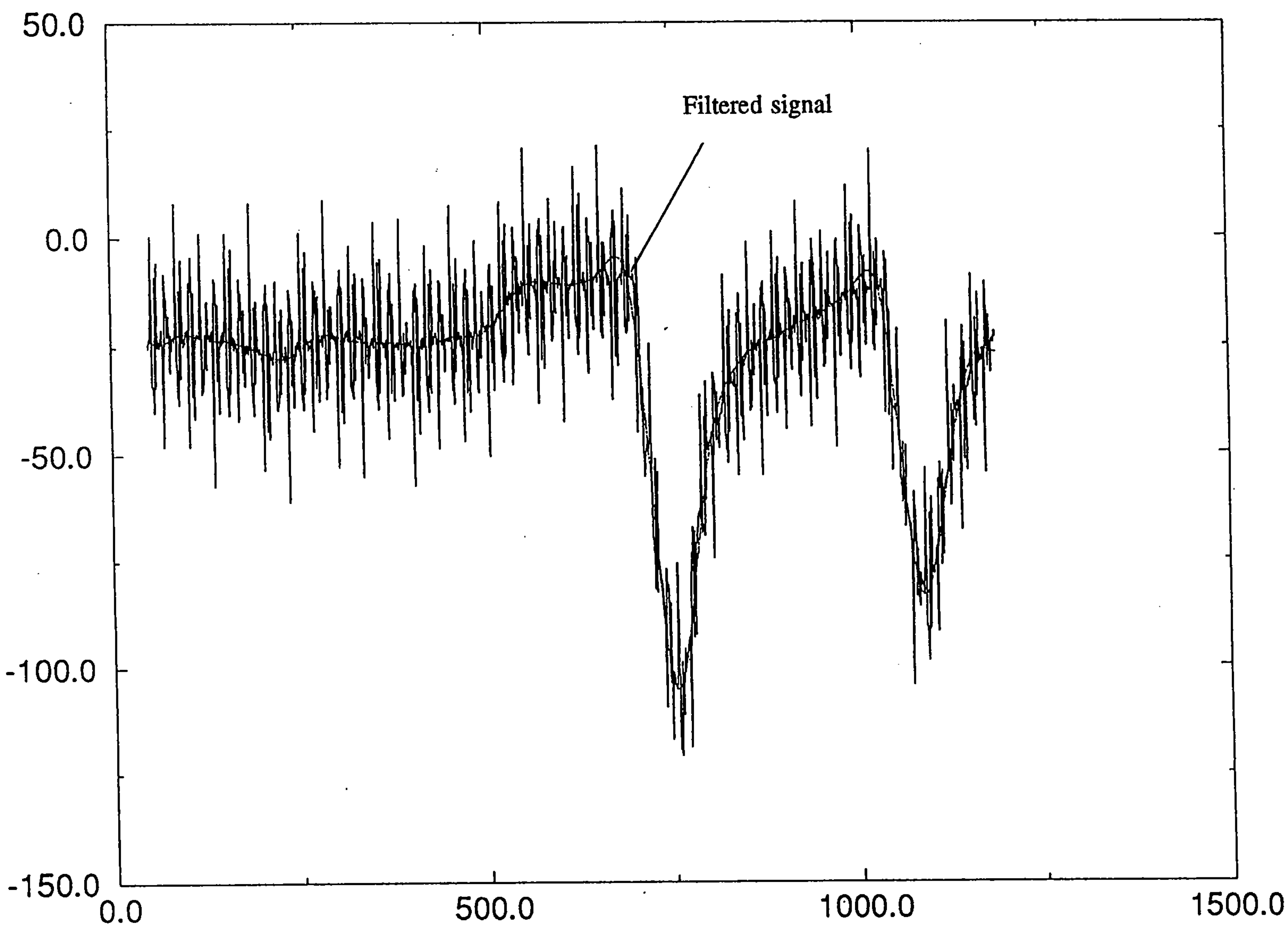
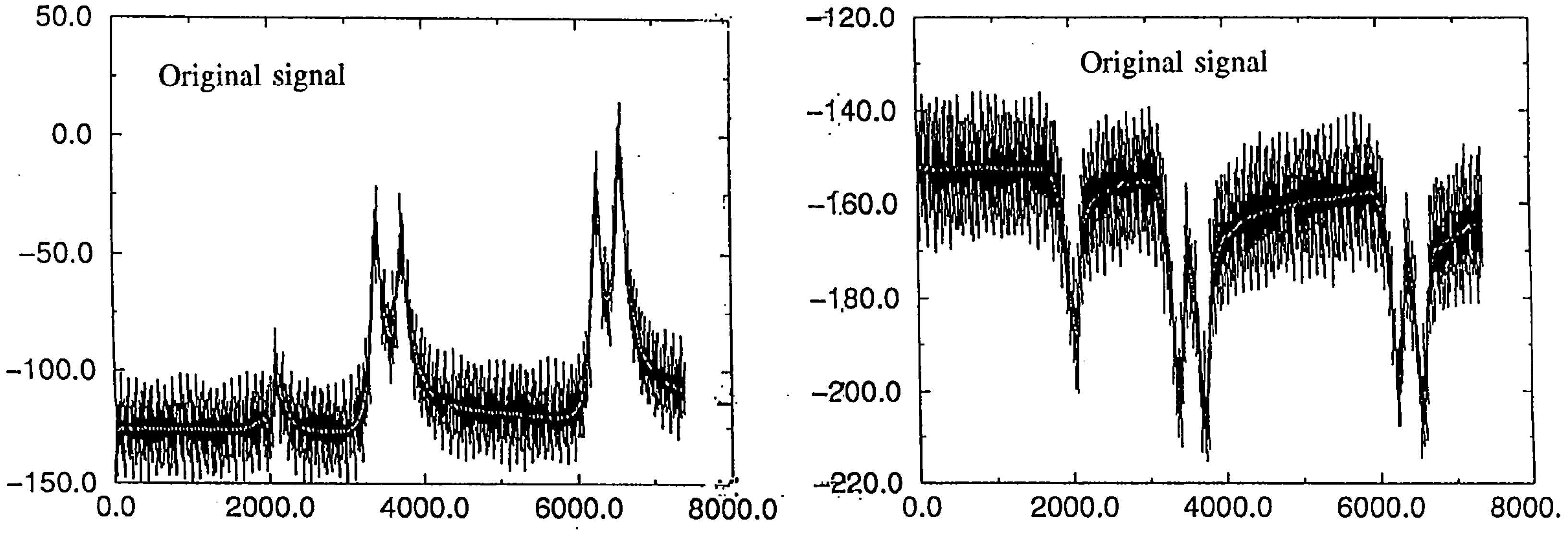


Figure 4. Superposition of an original and filtered signal.



(a) Tensile response

(b) Compressive response

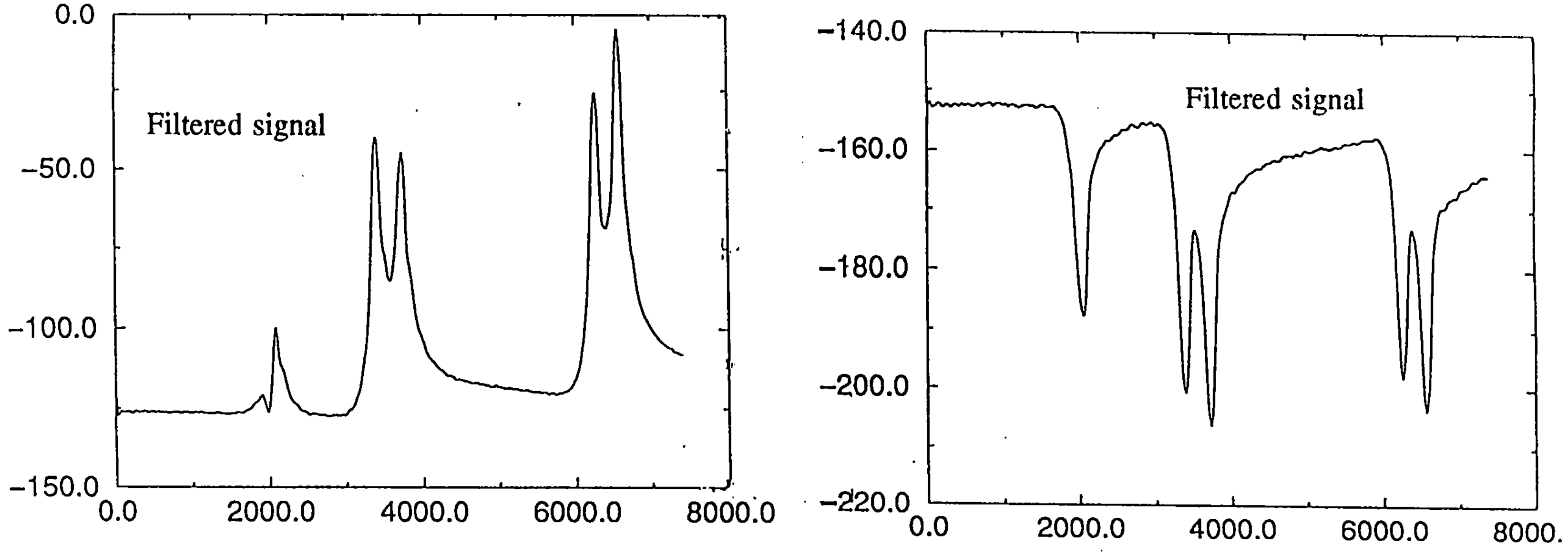


Figure 5. Comparison of filtered and original signals from a truck test.

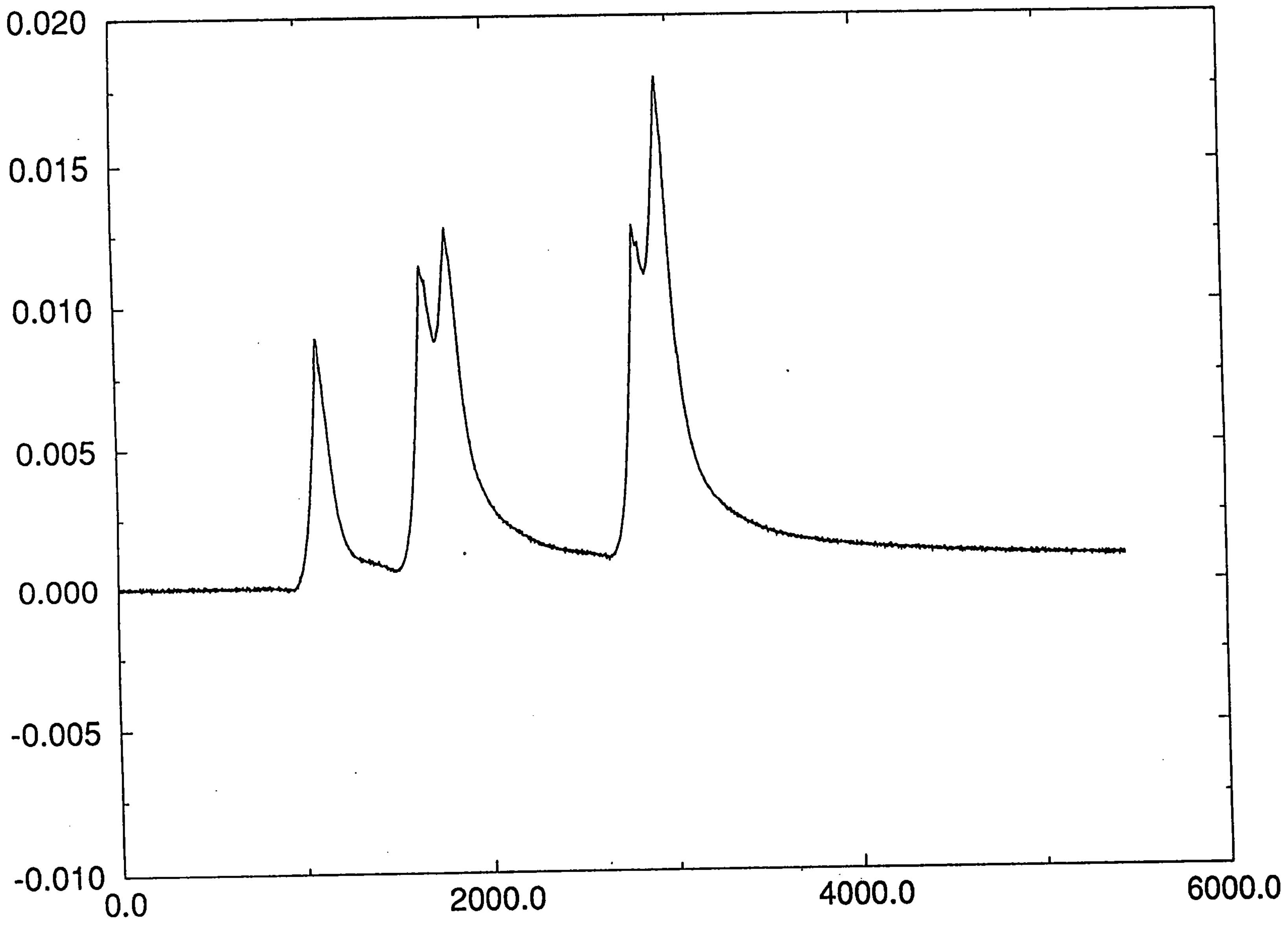


Figure 6. A less corrupted original signal.

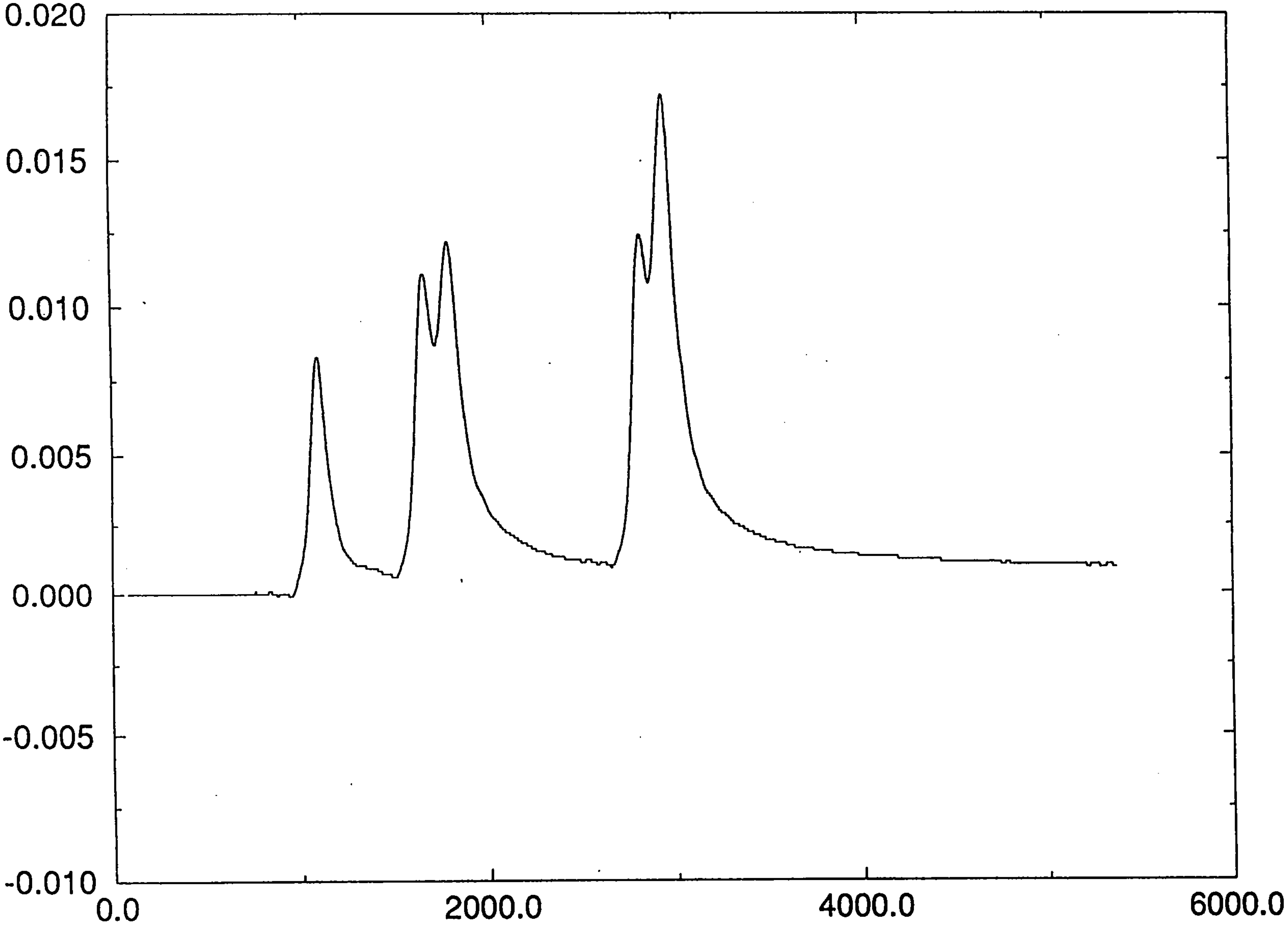


Figure 7. The filtered signal of the signal shown in Figure 6.

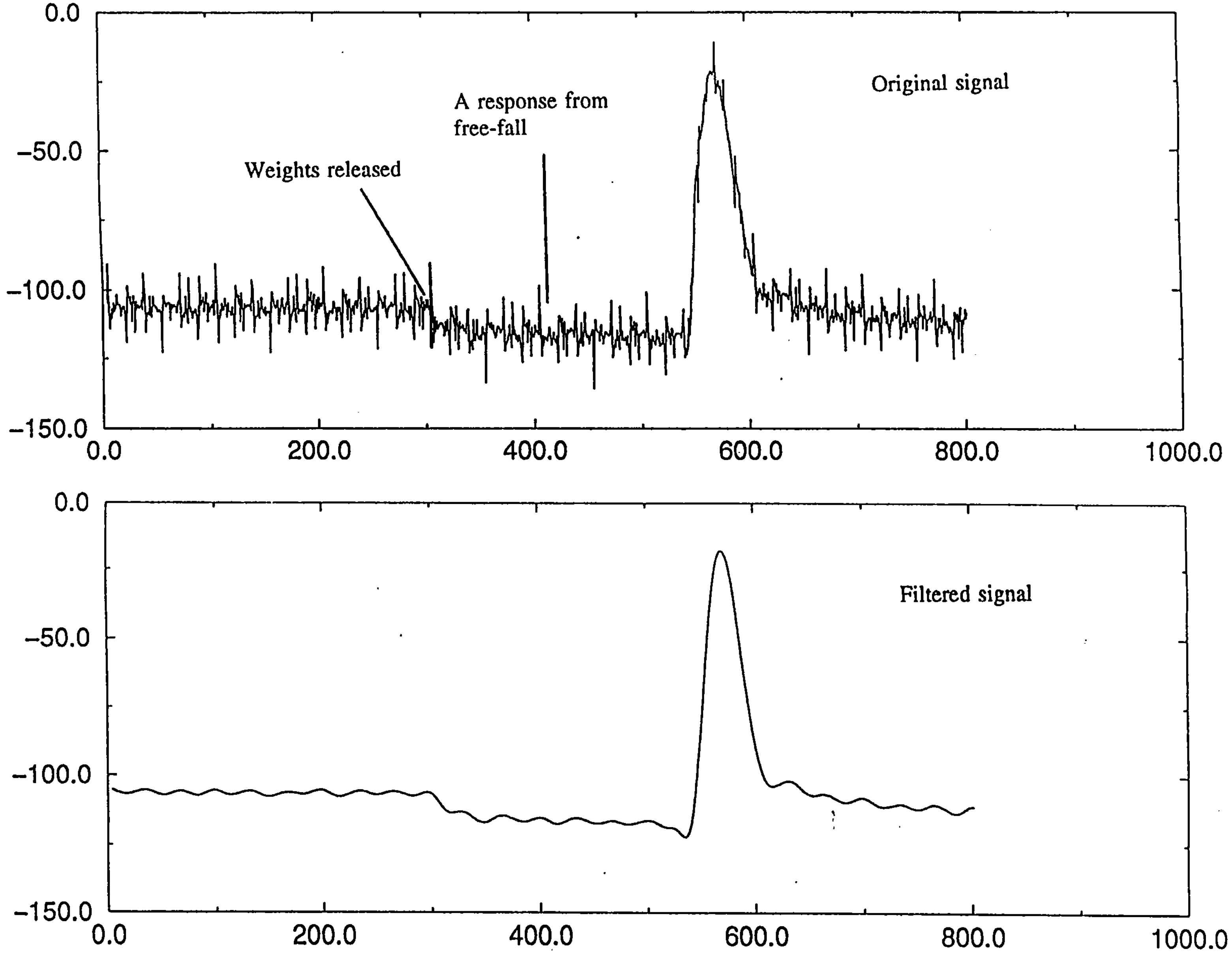


Figure 8. A typical sensor response from a FWD test (original and filtered signal)