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Compensation of Errors caused by Resonance Vibration of Measurement System in Impact Foıce Measurement

Y .Usui, S. Miyazawa and N. Sawai
Mechanical Engineering Laboratory, Namiki 1-2, Tsukuba-shi, 305 Japan

Abstract

When a force impulse acting on a massive and complex object is measured with a dynamometer, the resonant vibration of the measurement system often leads to serious inaccuracies. A more accurate measurement is obtained when the transfer function of the object-dynamometer system is used to compensate for the error in the dynamometer's output signal .

The natural frequency and the damping coefficient of the transfer function are estimated by analyzing the waveform of the free damped vibration period after the loading of the force has ended. The residue of the system is determined such that the compensated force spectrum becomes smooth within a neighborhood of the natural frequency.

The effectiveness of this signal processing method is experimentally tested on a hammer impulse, under the assumption that the hammer's high resonant frequency accurately models the problems encountered in force impact measurement. The compensation method is used to derive a improved estimate of the hammer impulse.

1. Introduction

Force measurements are often gathered using a dynamometer attached to the object upon which the force acts. The natural frequency of the object-dynamometer system is generally lower for a object of massive and complex shape than for one which is simple and light. As a result, the natural frequency overlaps with the frequency range of the measurement signal, and large measurement errors appear. Thus decrease in resonant vibration frequency can pose problems, especially in the measurement of high frequency impulse forces.

If the transfer function of the object-dynamometer system is measured ahead of time with a high resonant frequency impedance hammer, multiplication of the dynamometer signal by the inverse transfer function can produce an accurate impact force signal[1)-3)]. However, it is difficult to measure the transfer function when the structure of the system changes dynamically and/or the force loading point is not constant.

In this paper, we present a signal processing technique in which the transfer function is derived from the residual vibration of the system just after the loading of impulse force and used to adjust the dynamometer output The effectiveness of this procedure is verified experimentally.

2. Signal processing method

The discussion in this section mainly concerns signals in the frequency domain.

Dynamometer based force measurement systems do not measure the force signal F(s) directly. Instead, as shown Fig.1, the output consists of F(s) modified by H(s):

$$X(s) = H(s)F(s) \tag{1}$$

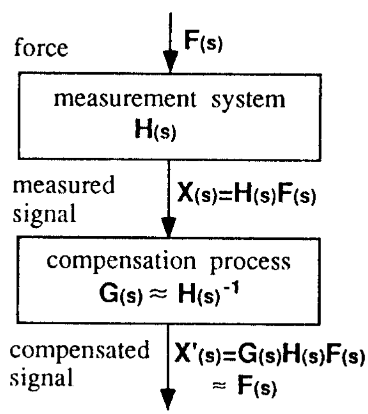

Fig.1 Force measurement and compensation process.

where H(s) is the transfer function of the measurement system, i.e. between the applied force and the output of the force dynamometer.

Given a function G(s) which closely approximates the inverse-transfer function of H(s), a good estimate X'(s) of the actual force signal F(s) can be obtained:

$$\begin{aligned} X'(s) &= G(s)X(s) \\ &\fallingdotseq H'^{-1}(s)H(s)F(s) \\ &= F(s) \qquad (2) \end{aligned}$$

In an ideal force measurement system, the resonant vibration is extremely high, and H(s)=1 throughout the frequency range of interest. However, in real applications the resonant vibration frequency of the measurement system is sometimes lower, introducing several poles into H(s) within the measurement range. As a simple example, we consider a 1-degree-of-freedom resonant vibration acting on an ideal measurement system, with a transfer function given by

$$H(s) = 1 + r/(s+p) + r^*/(s+p^*), \qquad (3)$$

where $s=i\omega$, $r=A-iB$, $p=\sigma-i\omega_0$.

Let us assume that the vibration of the object-dynamometer system is approximated by the linear damping system shown in eq.3, and that the impact force acts upon a single point on the object for a short time. Then the location of the poles of H'(s) (an approximation of H(s), equals to inverse function of G(s)) can be determined from the residual vibration of the system after the loading force has ceased. This is because the vibration during this period may be regarded as a free damping vibration, and the frequency and damping coefficient of the vibration depend upon the pole of H'(s). In addition we assume that the poles of F(s) and H(s) do not coincide, we can calculate the residue of H'(s) in a straightforward manner.

Details of the signal processing procedure are as follows:

A. Postprocess the Dynamometer Output Signal.

The dynamometer output x(t) is run through an A/D-converter and input to a personal computer, where its Fourier transform X(s) is calculated. We assume that the sampling domain $t_0<t<t_2$ of x(t) includes both the impact force and its succeeding residual vibrations.

B. Extraction of the Free Damping Vibration Interval.

The interval $t_1<t<t_2$ after the force has ceased to act on the object is determined. One approach to finding t_1 is to monitor the contact conditions at the impact point using electrical conductivity or optical

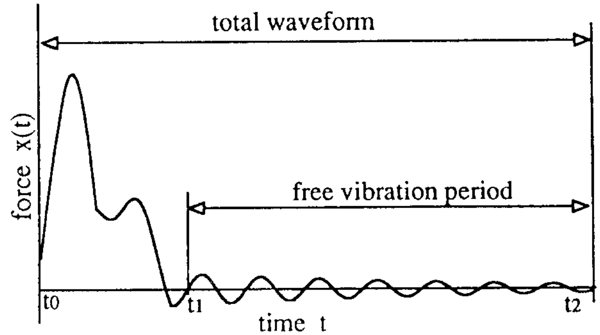

Fig.2 Typical output of force dynamometer for impulse force

interrupt methods. Another approach is to estimate the contact time from the dynamic characteristics of the location of impact. In many cases, t_1 can be more conveniently estimated using other criteria, as shown in Fig.2. In this case, we assume the impact force does not act after the dynamometer output reverses and crosses the zero point.

C. Determination of the Natural Frequency and Damping Coefficient.

Fig.3(a) shows the frequency domain representation X(s) for the waveform x(t) on the interval $t_1<t<t_2$. A standard curve-fitting technique is applied to X(s) to determine the position of its pole, which approximates the pole of the object-dynamometer system H(s).

D. Derivation of the Residue from the Total Waveform.

Because we have assumed that the power of F(s)

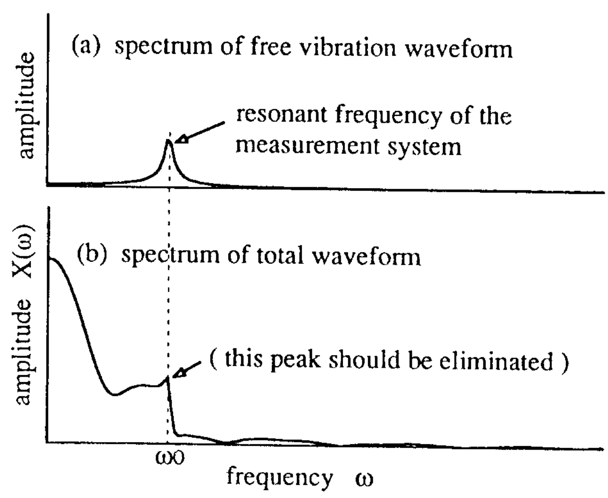

Fig.3 Frequency domain expression of free vibration period and total waveform

is not concentrated in a neighborhood of the system's natural frequency, the peak at ω_0 in Fig.3(b) must represent the resonant vibration of the object-dynamometer system. That is, the curvature of G(s)X(s), which is equivalent to the actual force F(s) acting on the object, must be small in a neighborhood of ω_0.

The residue of the transfer function H'(s) is decided by the least squares method, so that the curvature of G(s)X(s) is minimized in a halfpower half width of H'(s) at ω_0.

E. Recovery of the Power Signal.

The inverse Fourier transform on $X'(s) = G(s)X(s) = H'^{-1}(s)X(s)$ yields an improved estimate x'(t) for the actual impact force f(t).

3. Experimental verification of the signal processing method

The signal processing method is experimentally tested using the apparatus shown in Fig.4.

A KISTLAR 9257BU type dynamometer with a resonant vibration frequency of about 4kHz is used for the force measurement. The force is applied with PCB K291A04 type impulse hammer. High natural frequency of the impulse hammer over 50kHz guarantees accurate measurement of the impact force. Therefore, the output of the impulse hammer is used as a reference signal to evaluate the result of the signal processing.

Both the dynamometer output and the hammer impulse signal are AD-converted at a rate of 25k samples/s before being analyzed. The data length is 512 words. As shown in the figure, a vice holding a steel rod serves as the measurement object. The system's transfer function can be changed by adjusting the hanging length of the rod.

Fig.5 shows the reference signal from the impulse hammer, the output signal from the dynamometer and the signal processing results. In this case, the resonance frequency of the system is about 0.7kHz. Fig.6 illustrates the effects of a shorter hanging length, with a resonance frequency of 2.1kHz. The frequency domain expression of Fig.6 is shown in Fig.7.

4. Discussion

Fig.5 and 6 show that the natural frequency of the object-dynamometer system can be far lower than that of the dynamometer itself. Here, residual vibrations make accurate measurement of the impact force difficult.

In both cases, the compensation process was effective in suppressing the residual vibration signal. The amplitude of the vibration was reduced to about one-third that of the original signal. Some vibrations remained because the system had multiple poles, and some poles were left without compensa-

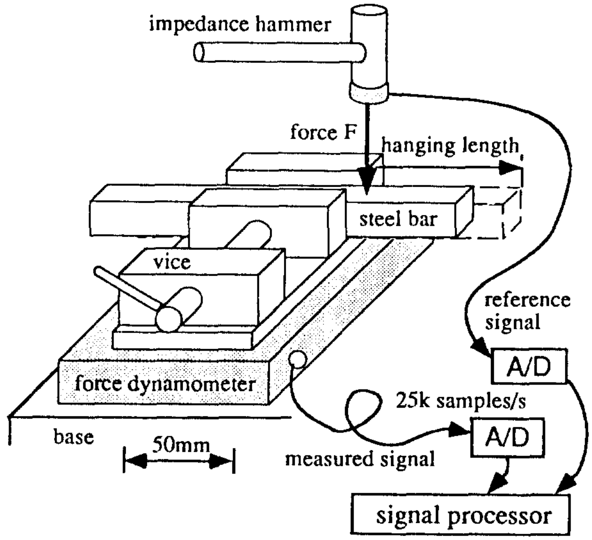

Fig.4 Experimental set up for impulse force measurement.

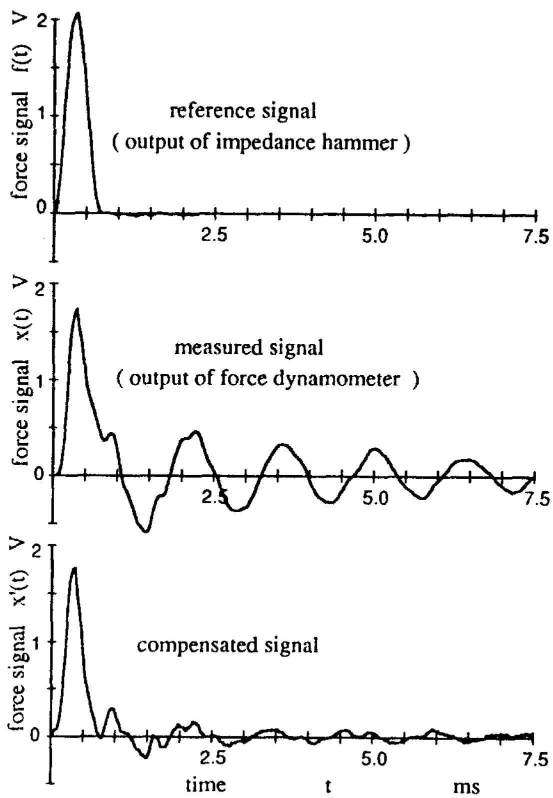

Fig.5 Result of force measurement and signal processing (hanging length = 100mm)

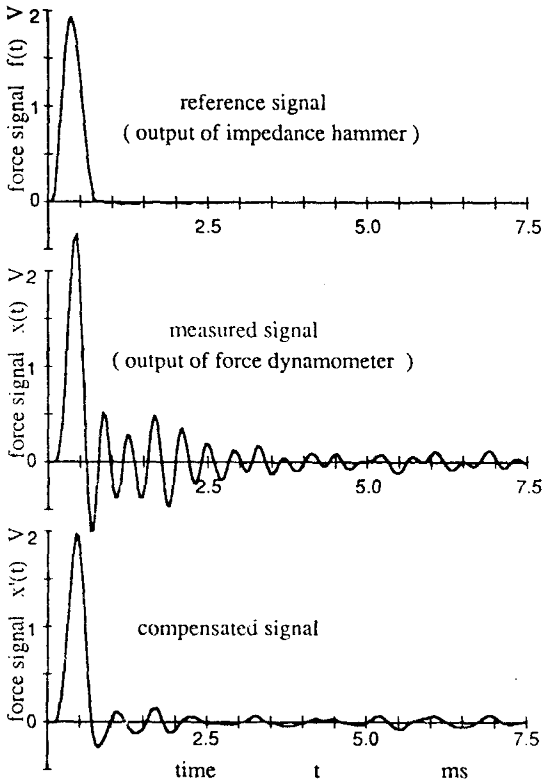

Fig.6 Result of force measurement and signal processing (hanging length = 50mm)

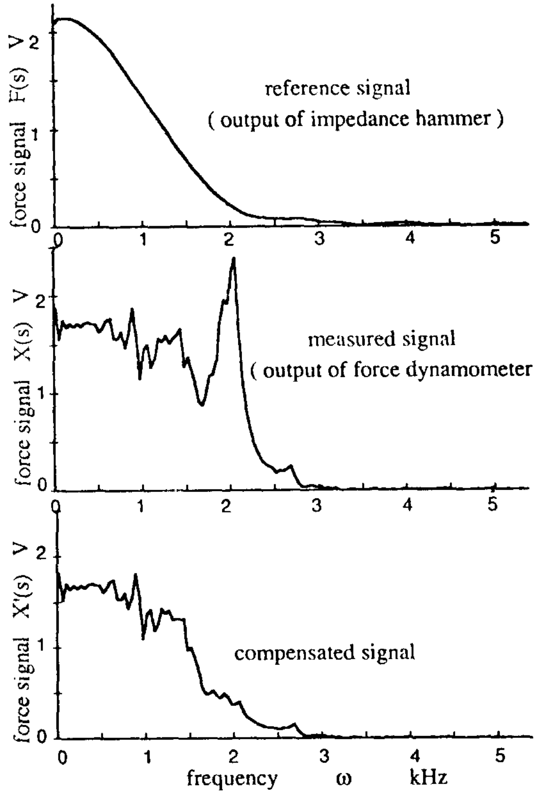

Fig.7 Frequency domain expression of the signals same as in figure 6 (amplitude)

tion. For example, Fig.7 shows the compensated signal still had an effect of resonance around 1.3kHz. When more than two resonant vibrations are encountered, free vibrations of multiple degrees should be assumed and the natural frequencies should be obtained using the procedure described in step *C*. For each resonant vibration, the residue may be calculated individually as in step *D*.

Through the compensation procedure, we obtained a reconstructed signal with a peak value closer to that of the actual hammer impulse. However, improvement of the wavewidth error was insufficient.

When the power of the force is concentrated near the natural frequency of the object-dynamometer system, high output at that frequency could potentially be misconstrued as an effect of the resonant vibration. To investigate this problem, it will be necessary to conduct experiments at various natural frequencies by adding an extra mass to the dynamometer.

5. Conclusion

In this paper we have presented a method for correcting impulse force measurement errors caused by resonant vibrations in dynamometer based measurement systems. The Fourier transform of the measured force signal is multiplied by the inverse transfer function of the object-dynamometer system. The pole of the transfer function is estimated through analysis of the resulting waveform during the free damped vibration period. And the residue is decided from the total waveform and the location of the pole.

We experimentally demonstrated the effectiveness of this procedure. The residual vibration signal was reduced to 1/3 of its original value during the compensation process. The peak value of the impulse force signal was also made closer to that of the actual force.

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