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DETERMINATION OF FLUID DAMPING USING RANDOM EXCITATION

Jackson C. S. Yang, Colin H. Marks, Jiesheng Jiang, Decheng Chen, Aliakbar Elahi, Wen-Hu Tsai
 Department of Mechanical Engineering
 University of Maryland
 College Park, Maryland 20742

ABSTRACT

An experimental investigation has been carried out to verify the validity of the use of the Random Decrement technique to determine the damping coefficients for a circular cylinder oscillating in water. Data are reported for amplitudes ranging from 0.4 diameters to 0.8 diameters, for water speeds from zero to 0.192 m/s (0.63 ft/sec), and for frequencies ranging from 0.37 Hz to 1.4 Hz. Comparison with other data, which has been reported in the literature or obtained by the authors, shows that the Random Decrement method yields comparable damping coefficients to those obtained using the logarithmic decrement technique for the range of variables in this experiment.

NOMENCLATURE

- \bar{c} = average damping factor per unit length of cylinder (gm/cm sec). Damping force/length = damping factor times velocity of cylinder
- c_v = $\bar{c}/\pi\rho v\beta^{1/2}$
- c_{visc} = $\rho\pi D\sqrt{2\omega v} + 2\pi\rho v$ (gm/cm sec)
- D = cylinder diameter (cm)
- n = frequency of periodic oscillation of the cylinder (Hz)
- \bar{u} = velocity of water current (cm/sec)
- X_0 = amplitude of oscillation (root mean square value for random oscillation)
- X_g = initial amplitude in displacement-time record (cm)
- α = X_0/D
- β = $\omega D^2/4v$
- ν = kinematic viscosity (cm²/sec)

- ρ = fluid density (gm/cm³)
- τ = length of time history (sec)
- ω = frequency of periodic oscillation of the cylinder (radians/sec)

INTRODUCTION

Measurements of fluid damping have generally been made by observing the decay of the amplitude of oscillations and using the logarithmic decrement technique (1,2,3). There is, however, another method, known as the Random Decrement technique, which can be used to obtain fluid damping coefficients. This technique was developed and explored initially by H. Cole (4,5) and continued by J.C.S. Yang et al. (6-9) and Aggour, et al. (10,11). Further analytical basis for the method has been given by Reed (12). The Random Decrement method advanced the state-of-the-art in the measurement of damping in structures subjected to random excitation when only response data is available. However, its validity for obtaining fluid damping coefficients has not been verified by direct comparison with results obtained using other methods.

This paper is concerned with comparing some damping coefficients for a circular cylinder obtained using the Random Decrement technique with the values obtained using the logarithmic damping technique. Measurements were made in both still water and in flowing water, with the plane of the oscillation being parallel to the current.

Because fluid damping coefficients are amplitude dependent (1,2), coefficients obtained from the logarithmic decrement technique, in which the amplitude decreases with time, must be corrected to give the result for constant amplitude oscillations. This was done for the work reported herein using the method described by Skop et al. (2).

Skop et al. found that the damping factor for cylinders oscillating in a still fluid were dependent

not only on the amplitude of the oscillation relative to the cylinder's diameter, but also on the frequency of oscillations. They correlated their results using three non-dimensional quantities. These were:

$$\text{Vibratory Reynold's number, } \beta = \omega D^2 / 4\nu \quad (1)$$

$$\text{Amplitude ratio, } \alpha = X_0 / D \quad (2)$$

$$\text{Damping coefficient, } c_v = c / \pi \rho \nu \beta^{-1/2} \quad (3)$$

Verley and Moe (1) made measurements of the damping factor of a circular cylinder oscillating at constant frequency in steadily-flowing water and found the non-dimensional quantity U/nD was important in addition to the amplitude ratio. They made no mention of the effect of the vibratory Reynolds number or of the steady-flow Reynolds number on their results, and they presented their results in terms of a dimensional damping factor rather than a non-dimensional damping coefficient.

Dimensional analysis applied to a cylinder oscillating in a steady current shows that there are four independent non-dimensional quantities. There are seven variables ($\rho, U, \omega, D, X_0, \nu, c$) and three dimensions (mass, length and time). Carrying out the dimensional analysis yields the following possible set of independent non-dimensional quantities:

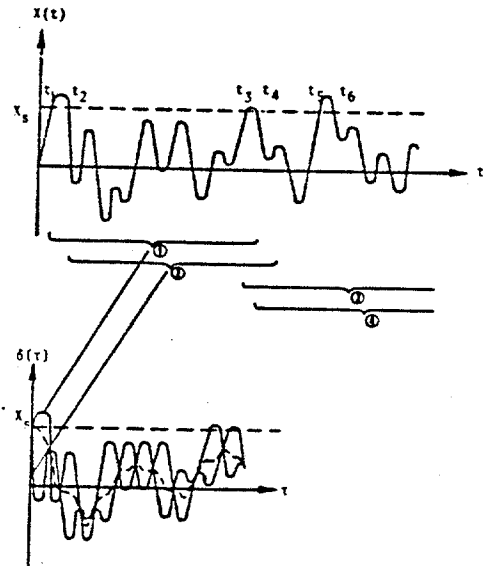
$$\frac{\rho U D}{\mu}, \frac{X_0}{D}, \frac{c}{\rho \nu} \text{ and } \frac{\omega D^2}{\nu}$$

Manipulation of these quantities makes it possible to obtain the non-dimensional groups c_v, α, β and $U/\omega D$ used by the previous investigators (n in U/nD was replaced by ω). This latter set was used to correlate the data in our experiments.

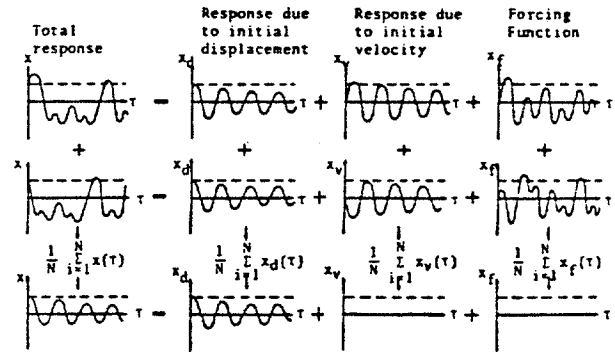
RANDOM DECREMENT TECHNIQUE

The Random Decrement technique was originally developed as a method for determining damping characteristics of models being tested in wind tunnels. Subsequently, the method was used to measure damping in buildings, machinery systems, etc.. It is currently used in the aerospace industry to measure damping in wind tunnel models and aircraft in flight. Also, small flaws (fatigue cracks, etc.) can be detected by monitoring the high-frequency characteristics of structures. This application is now under development for detection of cracks in highway bridges carrying traffic, and in offshore platforms. In fact, the technique is a general method of analysis that is applicable to the wide class of problems in which a system is subjected to an unknown random input and the only measured quantity is the system response. The procedure itself is a linear, ensemble-averaging technique that requires less computer time than the conventional spectral or correlation approaches.

The basics of the Random Decrement Technique are illustrated in Fig. 1. The fundamental concept of the "Random Decrement signature" is based on the fact that the random response of a structure is composed of two parts: a) a deterministic part (impulse and/or step function), and b) a random part. By averaging enough samples of the same random response, the random part will average out, leaving the deterministic part. It has been shown (5,12) that by proper digital processing, the deterministic part that remains is the free-decay response from which the damping can be measured. Hence, the Random Decrement Technique uses



Extraction of the Random Decrement Signature



Principles of Random Decrement Technique

Fig. 1 Basics of the Random Decrement Technique

the free-decay responses of a system under random loading to identify its vibration parameters; namely, frequencies and damping.

Figure 1 shows the procedure for obtaining a signature. A time history (velocity, acceleration, strain or displacement, etc. versus time) is divided into an ensemble of segments of equal lengths, τ_{max} , each beginning at a selected amplitude x_s (or for example, X_0 , if the time history is in terms of acceleration). Also, the segments are chosen such that half the segments have an initial positive slope and the other half have an initial negative slope. These segments are then ensemble averaged to give a signature of length τ_{max} whose initial amplitude is x_s . The initial slope is zero since an equal number of positive and negative slopes will, for most systems, average to zero.

For a linear, single-degree-of-freedom system, the

signature becomes the damped cosine wave describing the motion when the system is subjected to the initial displacement x_0 and then released. In practice, however, linear systems have many degrees of freedom and the signature is of a combination of modes, although it still represents the free vibration response to an initial displacement. For multi-mode problems, the response records are bandpass filtered to isolate different frequency bandwidths. Damping values are calculated for each case to obtain the variation of damping with amplitude and frequency. For nonlinear systems, the signature represents the free-vibration response of a system in which the nonlinear properties are averaged to a value dependent on the amplitude.

The starting value x_0 can be chosen arbitrarily. The freedom to select the initial value (bias level) is one of the main advantages of the method. If the record is nonstationary and contains periods of low level vibration in which the signal-to-noise ratio is very low, the initial amplitude can be chosen above this level and the low-amplitude portion of the record is disregarded.

The accuracy of the signature depends on the record length in terms of the number of cycles of data. The convergence is fast, which is important when analyzing records of marginal length.

The advantage of the Random Decrement Technique is that it is a simple, direct, and precise method for translating the response-time history into a form meaningful to the observer. In comparison to the spectral power density method, where damping is measured by the half-power bandwidth method, it has been found that the spectral density method shows a large measurement variance, especially when the bandwidth is small or the spectral peak is well defined. In addition, when two modes are close, the classical method cannot be applied. In the Random Decrement Technique, as part of the analysis, the records can be filtered to isolate modes if the modes are not too close together. When the modes are close together, a numerical curve fitting technique can be applied to the Random Decrement signature to separate the modes and extract the damping ratios.

Since, in the Random Decrement method, the cylinder is subjected to a random force, its displacement-time history is random. The question then arises as to what amplitude to use to correlate the damping data. Experience in this and other work has shown that the root-mean-square value yields good results.

As mentioned above, the resulting signature, after processing of the random output, is a damped cosine wave describing the motion when the system is given an initial displacement x_0 and released. The frequency of this motion is the quantity ω which appears in β and in $U/\omega D$ for the Random Decrement data.

APPARATUS

Measurements were made using the pendulum type apparatus shown in Figure 2. The entire pendulum, including the weights and the cylinder, swung as a rigid body. There was considerable bracing to make the apparatus rigid, but this was not shown in Figure 2 for the sake of clarity. The natural frequency of the pendulum, and hence the frequency of the periodic motion of the cylinder, ranged from 0.37 Hz to 1.4 Hz. It was changed by connecting horizontal springs between the arms and a fixed anchor point, and by changing the

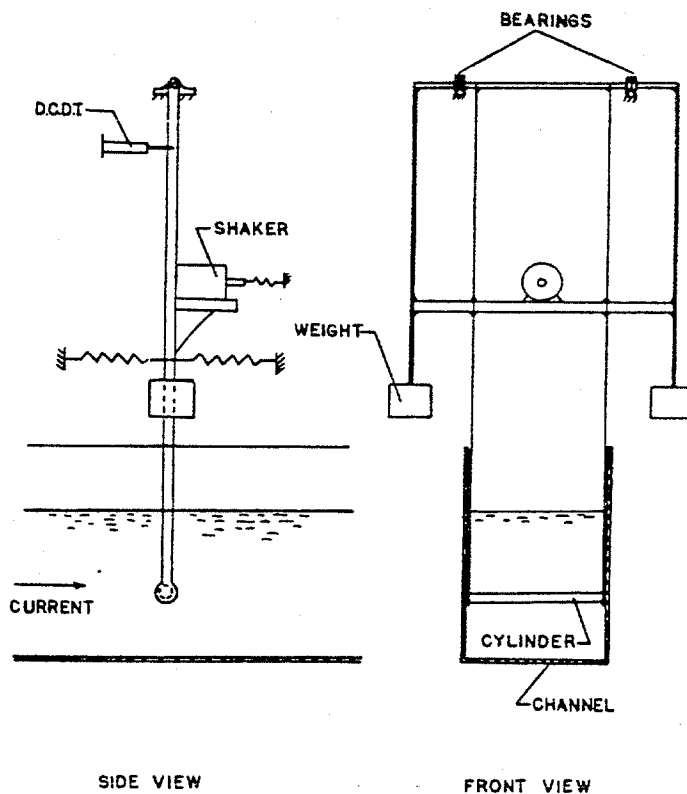


Fig. 2 Apparatus

position of the weights. The quantity $U/\omega D$ was varied by changing both U and ω . For the logarithmic decrement measurements, the pendulum was allowed to swing freely; however, for the Random Decrement measurements, a random force was applied to the pendulum by a hydraulic cylinder. In both cases, the amplitude as a function of time was obtained using a direct-current differential transformer (DCDT). In the case of the logarithmic decrement measurements, the output of this DCDT was fed to a strip chart and the data were reduced using the curve-fitting technique described by Skop et al. (2). For the Random Decrement measurements, the DCDT output was fed to a magnetic tape and the signal was processed by a Random Decrement Structure Monitor. The random force applied to the apparatus was white noise having a frequency range of approximately zero to 1000 Hz. At least 500 samples of the output were averaged to obtain a damping factor.

The channel in which the tests were run was 0.61 m (2 ft.) wide and the water was 0.61 m (2 ft.) deep. The current was uniform and its speed could be varied from zero to 0.21 m/sec (0.7 ft/sec). The cylinder was smooth, had a diameter of 2.54 cm (1 inch), and spanned the channel with about a 1 mm clearance between the thin, flat supports at its ends and the walls of the channel. The large aspect ratio and the close clearance between the ends of the cylinder and the channel walls insured that end effects were negligible. Because of the long cylinder supports (2.8 m), the curvature of the path of the cylinder was very small.

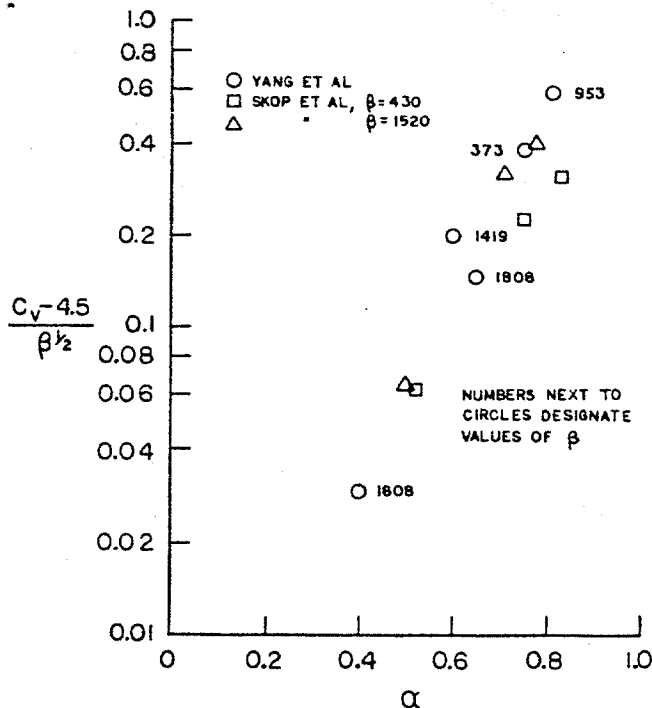


Fig. 3 Damping coefficients for still water

The measurements reported herein were all made with the cylinder centered between the surface and the ground plane. Measurements of the damping as a function of distance from the ground plane and from the surface (to be reported elsewhere) showed that the cylinder was sufficiently far from either that the damping was not affected by their proximity. The intensity and scale of turbulence was not measured, but dye streaks in the water showed very little mixing, so the free-stream turbulence was quite small.

Damping was determined both with the cylinder in place and with it removed. The latter was done in order to obtain the damping of the apparatus. The apparatus damping was subtracted from the total damping so as to yield the damping due to just the cylinder.

RESULTS AND DISCUSSION

The first comparison of the data was made with that of Skop et al. (2) for still water. Since only five data points were obtained in still water, insufficient data were obtained to draw families of curves. Further, Skop et al. show only two sets of data, one for $\beta = 430$ and another for $\beta = 1520$. However, comparison with Skop et al.'s data was still possible since they suggest that, for α greater than some value α_T , the data can be correlated by means of an equation of the form

$$\frac{c_v - c_1}{\beta^{1/2}} = \frac{16}{3\pi} 2c_2(\alpha - \alpha_T) \quad (4)$$

where c_1 , c_2 and α_T are coefficients which depend on β . Further, they state that the total variation in these coefficients is very small over the range $230 < \beta < 5220$ and that they may be considered essentially constant. The average values given by Skop et al. for the coefficients are

$$\begin{aligned} c_1 &= 4.5 \\ c_2 &= 1.68 \\ \alpha_T &= 0.4 \end{aligned}$$

A plot of our data and six randomly chosen data points from Skop et al. is shown in Figure 3. In this figure the data are plotted in the form $(c_v - c_1)/\beta^{1/2}$ versus α , where c_1 is set equal to 4.5. It is seen that there is good agreement between our data and that of Skop et al..

It should be noted that comparison was not made between our data and equation (4) since the equation with values of the constants given by Skop et al. does not fit their data as well as one would desire for comparison purposes, though it may be sufficiently accurate for estimating damping factors over a wide range of α 's and β 's.

The data for the cylinder oscillating in the flowing fluid were not as easy to compare as those for the still fluid, since there are four non-dimensional variables for this case (requiring much more data) and we have no satisfactory equation for correlating the data. Thus, comparisons were made between data obtained using the Random Decrement technique and those obtained using the logarithmic decrement method for the nearest combination of α , β and $U/\omega D$ that was available. The data compared are shown in Table 1. In accordance with the procedure outlined by Verley and Moe (1), the values of c_v in this table are based on the damping factor minus the viscous term, $c_{v,visc}$, where

TABLE 1 - Damping in Moving Water

Random Decrement				Log Decrement			
α (rms value)	$\frac{U}{\omega D}$	β	c_v	α	$\frac{U}{\omega D}$	β	c_v
0.32	1.05	1101	20.5	0.3	0.92	919	20.3
0.48	0.82	1401	42.0	0.5	0.92	919	41.9
0.47	3.25	370	92.8	0.5	3.18	445	102.0
0.49	2.07	370	62.3	0.5	2.11	418	56.6
0.72	1.23	941	48.5	0.7	0.92	919	40.4
0.72	1.05	1101	39.8	0.7	0.92	919	40.3

$$c_{v,visc} = \rho \pi D \sqrt{2\nu\omega} + 2\pi\nu\omega \quad (5)$$

Thus c_v in this table is given by

$$c_v = \frac{\bar{c} - c_{v,visc}}{\pi\rho\nu\beta^{1/2}} \quad (6)$$

Again, the data appear to be in good agreement.

Inspection of Table 1 shows that c_v increases with increasing α , increasing β and increasing $U/\omega D$. Skop et al. showed that c_v was directly proportional to the square root of β for a given α for still water. Thus, in still water, increasing β at large values of β has a much smaller effect on c_v than at small values of β . The quantitative effect of β on c_v in flowing water is currently under investigation and is not yet known. Both Skop et al. and Verley and Moe showed that the damping increases with increasing α , and Verley and Moe showed that it also increases with increasing $U/\omega D$. These trends are also seen in the data shown in Table 1.

It is of interest to note that the Random Decrement method, using the root-mean-square value for the amplitude, yielded good results even though the oscillations were large, and, according to Skop et al.'s measurements, the damping in this range is non-linear.

SUMMARY

The Random Decrement technique was used to determine the damping coefficients for a circular cylinder oscillating in water. Comparison of the coefficients so obtained with those obtained using the logarithmic decrement technique showed good agreement both in still water and in a uniform, steady current. The amplitude of the oscillations ranged from 0.4 to 0.8 diameters, which is in the non-linear range for the vibratory Reynolds number at which measurements were made. The damping factor was seen to increase with increasing amplitude of the oscillations, with increasing vibratory Reynolds number and with increasing, non-dimensionalized, current velocity.

ACKNOWLEDGEMENT

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