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DEVELOPMENT OF A PROTOTYPE CIRCUIT FOR VISCOUS DAMPING MEASUREMENT

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Abstract. *This paper presents the development of a prototype circuit that measures the damping coefficient of a fluid-solid interface. By means of the under damped motion of a mass, it is possible to measure the damped angular frequency of the system, which is directly related to the damping ratio, originated by the fluid viscosity. A wireless sensing method is proposed, using an accelerometer, a microcontroller unit and two radio modules. Such an approach can yield an implementation that is flexible and adaptive to industrial and scientific applications.*

Keywords: *damped, Reynolds, accelerometer, radio, motion.*

1. INTRODUCTION

Vibration detection and control is a relevant topic of research both academically and in industrial applications. The word is derived from Latin *vibrationem*, meaning “shaking” or “tremble”, which relates to the physical phenomenon where oscillations occur around an equilibrium point. Such motion can be desirable, for example, in musical instruments and medical applications, where controlled resonance is intentionally induced to produce a measurable response signal used to detect diseases and malfunctions of internal organs. When not desirable, however, it may threaten the integrity of structures and decrease the life time of mechanical components, soaring the costs of operation and maintenance of industrial plants.

Careful designs and vibration analysis usually minimize unwanted vibrations. It is important, thereby, knowing the parameters that affect the vibration of the system. The three main parameters of the vibrating system are the inertial parameter, the elastic characteristic and the damping coefficient. Among all the mentioned parameters, the viscous damping involves the greatest difficult to be measured, because it usually consists of fluid-solid interfaces, which in general do not have a simple method of measurement. Several methods have been proposed for damping calculation, such as experimental modal analysis (Ewins, 1984; Maia and Silva, 1997a; Maia, *et al*., 1997), linear least-square method and finite element analysis (Duffour, 1998; Chang and Nghiem, 2010). Although very precise and flexible, these methods use advanced mathematical concepts and computational resources, requiring numerical convergence and a deep programming background.

The method presented in this article describes an approach that is easy to adapt to industrial environments, as well as scientific applications. The electronic circuit used can be developed on a tiny printed circuit board, containing low cost and low power components, turning it into a very adaptive tool. No specific knowledge is required, since the software makes all the calculations needed, and outputted data are ready to be interpreted. The wireless feature provides flexible data collection over a range of 20 meters.

2. BACKGROUND

In classical mechanics, an oscillator is a physical system that experiences a restoring force when disturbed from its equilibrium position. If the force is proportional to the displacement, the system is called a harmonic oscillator, and the motion can be described by:

$$m\ddot{x} + kx = 0 \tag{1}$$

Where *m* is the system mass, $\ddot{\boldsymbol{x}}$ is the acceleration vector, *k* is a positive constant (spring stiffness) and $\boldsymbol{x}$ is the displacement vector. In real applications, however, the friction usually exerts an influence over the motion of the system. For low Reynolds number, the viscous resistance can be modelled according to Stoke's drag law, resulting in a damped equation of motion:

$$m\ddot{x} + b\dot{x} + kx = 0 \tag{2}$$

where b is a constant that depends on the geometric parameters of the object and the properties of the fluid. The solution for Eq. (2) is given by:

$$x(t) = e^{-\xi\omega_n t}\left[x_0\cos(\omega_d t) + \frac{1}{\omega_d}(\xi\omega_n x_0 + \dot{x}_0)\sin(\omega_d t)\right] \tag{3}$$

where x_0 is magnitude of the initial displacement, $\dot{x}_0$ is the magnitude of the initial velocity,

$$\xi = \frac{b}{2\sqrt{mk}} \tag{4}$$

is the damping ratio,

$$\omega_n = \sqrt{\frac{k}{m}} \tag{5}$$

is the natural angular frequency of the system and

$$\omega_d = \omega_n\sqrt{1 - \xi^2} \tag{6}$$

is the damped angular frequency.

2.1 Methodology

The foundation of the method consists in finding the dependence between the damping coefficient and the damped angular frequency of the system. Substituting Eq. (4) and Eq. (5) in Eq. (6) we obtain:

$$b = 2\sqrt{mk\left(1 - \frac{{\omega_d}^2}{{\omega_n}^2}\right)} \tag{7}$$

Equation (7) exhibits a relation between the viscous damping coefficient and the damped/natural angular frequencies of the system. Since ω_n only depends on internal parameters *k* and *m*, the damped angular frequency ω_d can be measured by an external agent so that the value of *b* can be determined. Figure 1 shows a general case of oscillation and the points that are considered for calculating ω_d.

Every time the mass passes through the equilibrium point (zero acceleration), the system triggers a stopwatch that stops when the equilibrium point is reached again. The amplitude of the motion does not need to be considered, since the viscous damping coefficient has no dependence on it.

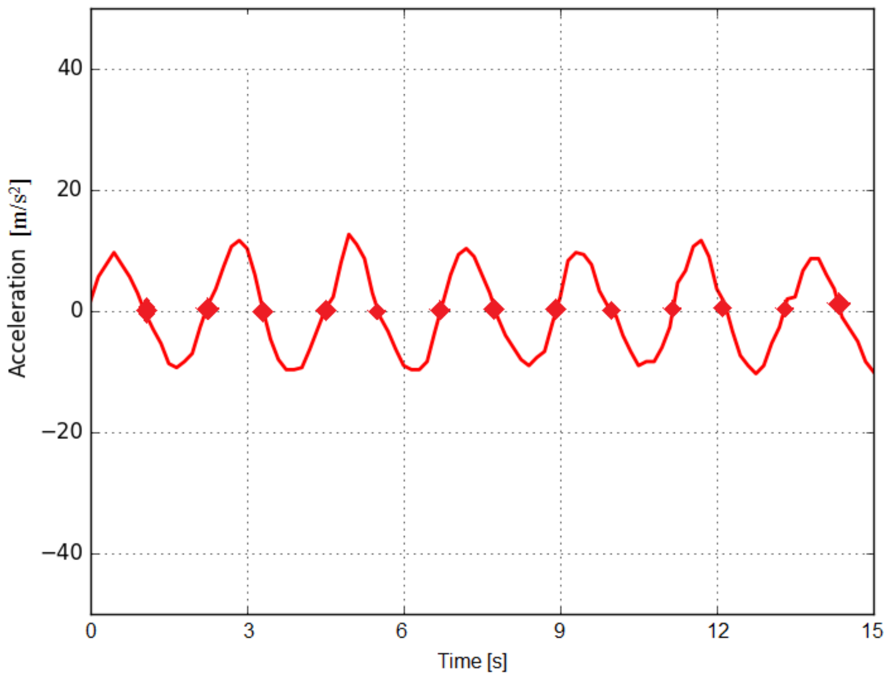

Figure 1. Equilibrium points.

The spring stiffness constant was obtained through a linear regression fit containing 10 data points, whereas the mass was determined using a precision balance with a 0.001 kg precision. Table 1 shows the data points for spring stiffness calculation.

The curve fit model results in $\boldsymbol{k}$ = 130.75 N/m. The value for the total mass of the system is $\boldsymbol{M}$ = 1.025 kg. The natural angular frequency $\boldsymbol{\omega_n}$ = 11.29 rad/s.

Table 1 – Load vs. displacement of the spring.

Load (N)	Length (m)
0.0	0.02
2.32	0.028
3.94	0.041
4.95	0.048
6.29	0.061
7.36	0.068
8.23	0.07
10.45	0.093
11.49	0.103
13.00	0.114

2.2 System for data acquisition

The detection of the damped angular frequency requires an electronic circuit that is capable of counting how many times the mass passes through the equilibrium position. Once the movement has started, a stopwatch is triggered and a Python based algorithm keeps track of how many oscillations have occurred in a certain amount of time. Once ω_d is calculated, and since the spring stiffness constant and the mass are predetermined, the viscous damping coefficient can be calculated from Eq. (7).

For more reliable information, the measurement is usually repeated over a different number of oscillations, ranging from 10 to 60 cycles. A linear regression curve fit adjusts the data for best approximation. Since the baud rate varies from 9600 to 115200 bps, the input signal can only be detected reliably if its frequency is no greater than 57.6 kHz (Nyquist–Shannon sampling theorem). In real applications, however, the sampling frequency must be about 5 to 10 times the frequency of the input signal (Fadali and Visioli, 2013), due to time delays that occur during the transmission, caused by serial buffer and ADC errors. Figure 2 shows the data flowchart throughout the system.

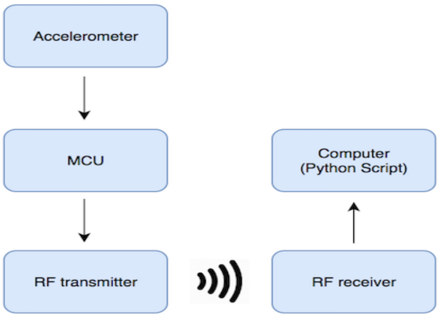

Figure 2. Measurement flowchart

The mechanical components are assembled in such a way that they compose a series mass-spring-damper system. Figure 2 shows the mechanical assembly of the system.

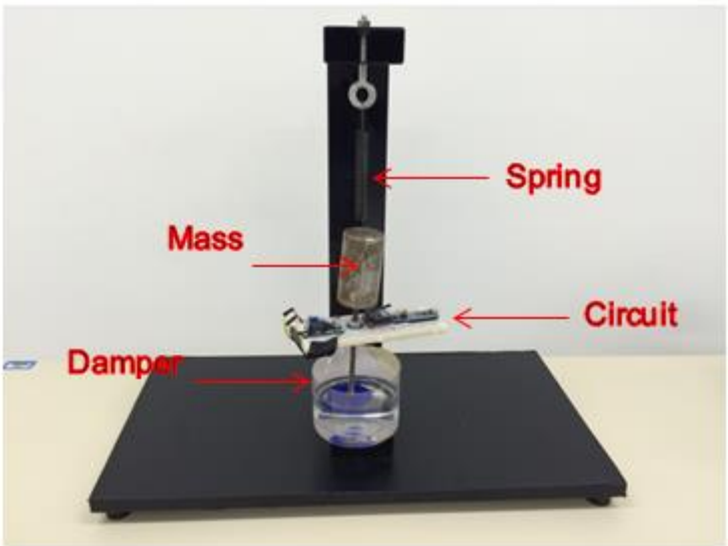

Figure 3. Mechanical components.

2.3. The electronic circuit

The prototype electronic circuit is based on an Arduino nano microcontroller, which has an affordable cost and provides a friendly user interface. The acceleration data is obtained using a 3 axis accelerometer ADXL335, with two XBee S2 radio modules configured as a two node wireless network. A DC boost converter was used to raise the voltage from 3.6 to 5 Volts. The circuit drains 300 mA at 3.6 Volts, resulting in 1.08 Watts consumption. Figure 3 shows the real electronic circuit.

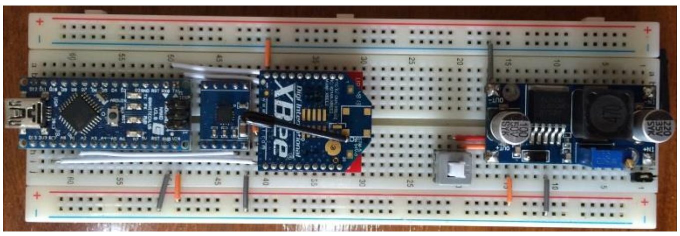

Figure 4. The electronic circuit.

3. EXPERIMENTAL RESULTS

In order to demonstrate the efficiency of the prototype measurement, different experiments were performed considering three different fluids, i.e., air water and soy oil. All the experiments were conducted in a laboratory room at 68 ºF (20 ºC) and 100.88 kPa of atmospheric pressure.

Figure 5 illustrates the experiment considering air as the fluid.

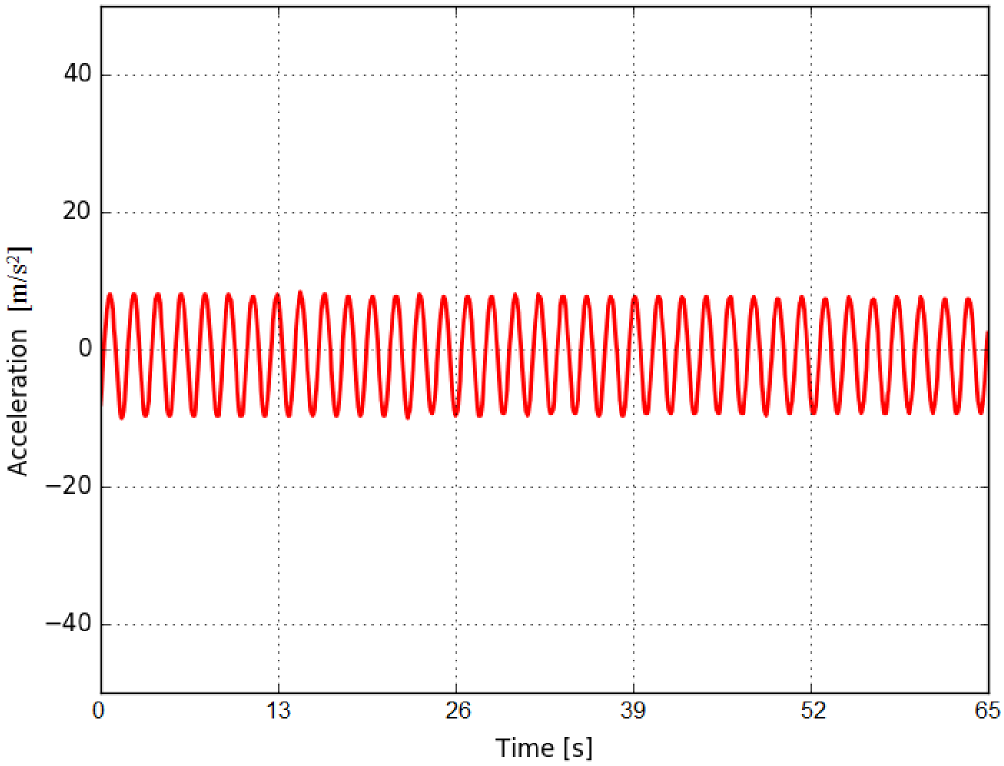

Figure 5 Measurement of oscillation for air.

It is important to emphasize the low viscosity of such a fluid. The damping is negligible for few oscillations. The results for the damped angular frequency and the viscous damping coefficient obtained from Fig. 5 are presented in Table 2:

Table 2. Results for air.

oscillations	Time (s)	Frequency (Hz)
10	5.55	1.80
20	11.27	1.77
30	16.86	1.78
40	22.51	1.77
50	28.09	1.78
60	33.78	1.78
$\boldsymbol{\omega_d}$	11.15 rad/s	-
$\boldsymbol{b}$	3.73 Ns/m	-

The number of oscillations considered ranges from 10 to 60. This approach allows more accurate results, since it evaluates the motion from the beginning to the end, and it also shows that damped frequency remains almost constant throughout the execution of the experiment.

The result for the experiment using water is shown in Fig. 6.

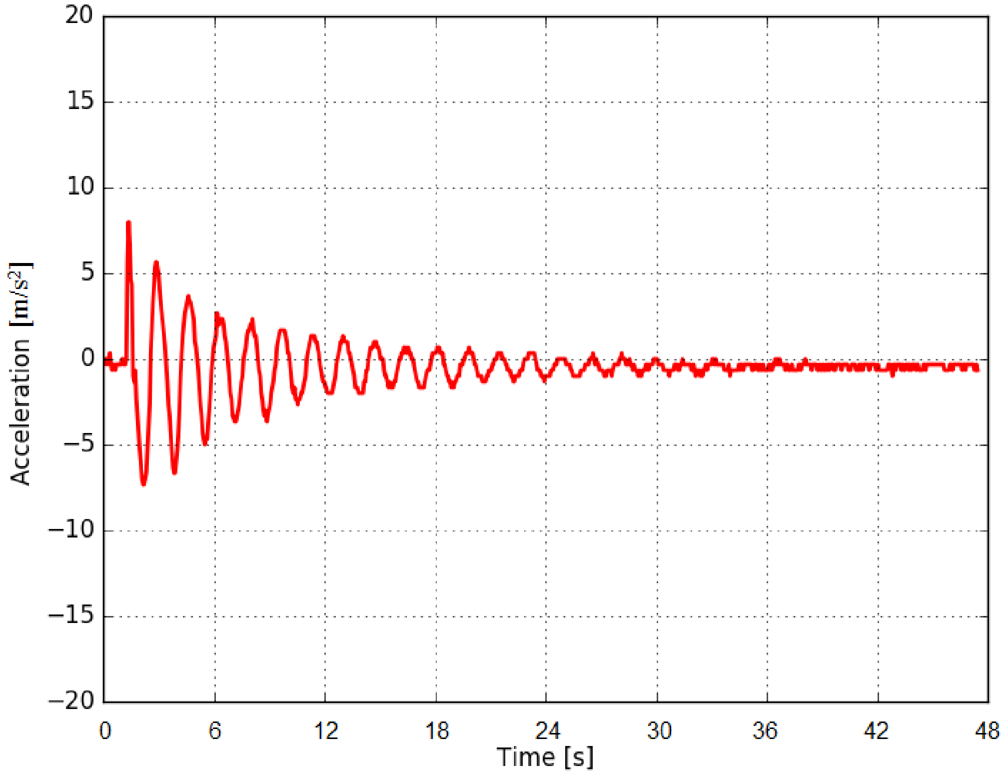

Figure 6. Measurement of oscillation for water.

Water shows a more significant damping than air, since liquids tend to be more viscous than gases in general. The results for the damped angular frequency and the viscous damping coefficient obtained from Fig. 6 are presented in Table 3:

Table 3. Results for water.

oscillations	Time (s)	Frequency (Hz)
10	5.74	1.74
20	11.42	1.75
30	17.34	1.73
40	23.09	1.73
50	28.82	1.73
60	34.53	1.74
$\boldsymbol{\omega_d}$	10.89 rad/s	-
$\boldsymbol{b}$	6.15 Ns/m	-

Water has a damping coefficient 64.88% greater than air. The damped angular frequency for water, however, is 2.33% lower than air.

Through Fig. 7 it is possible to verify the result for the fluid soy oil.

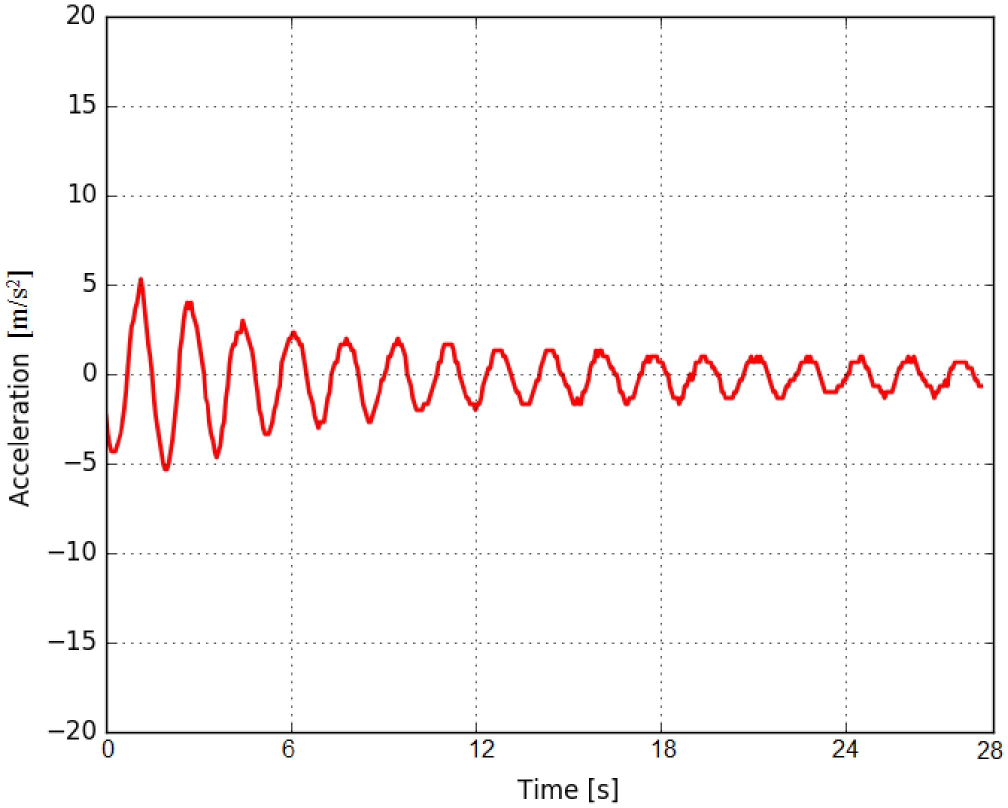

Figure 7. Measurement of oscillation for soy oil.

The results for the damped angular frequency and the viscous damping coefficient obtained from on Fig. 7 are presented in Table 4:

Table 4. Results for soy oil.

oscillations	Time (s)	Frequency (Hz)
10	5.69	1.80
20	11.51	1.77
30	17.45	1.78
40	23.26	1.77
50	29.06	1.78
60	34.81	1.78
$\boldsymbol{\omega_d}$	10.78 rad/s	-
$\boldsymbol{b}$	6.93 Ns/m	-

As expected from theory (Rao, 2004; Den, 1985), the viscous damping factor of soy oil is greater than water and air due to the fluid viscosity, which tends to be more significant in liquids than it is in gases. The great number of oscillations considered contributes to an even evaluation of the frequency, lasting from the beginning of the motion until the complete stop of the movement.

4. CONCLUSIONS

Modal analysis is the most frequent method for solving vibration problems in engineering. Togheter with finite element method and numerical simulation, these approaches are capable of solving the majority of the problems involving damped vibrations. Even though these are popular methods, they involve complex mathematical, physical and computational background, as well as they can take great amounts of time and financial resources to be concluded. This paper has presented an alternative methodology for measuring the viscous damping effect, based on a low cost protoype, using algorithms which were implemented on a free Python distribution. Its applicability was evidenced through experiments which presented satisfactory results for different types of fluids: air, water and soy oil. As further work there exists the need of comparing the obtained values with a theoretical model of a viscous damper, which relates the damping coefficient with the viscosity of the fluid used.

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