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Validation of dynamic modelling of an industrial vibratory bowl feeder

Marcos A. Felizola[1], Álvaro M. S. Soares[2,3]*, João B. Gonçalves[4] and Pedro P. L. Prado[4]

[1]SENAI-SP – Brazil.
[2]Department of Mechanical Engineering, University of Taubate, Taubate, Brazil.
[3]Department of Mechanics, UNESP – University of Estadual Paulista, Guaratinguetá, Brazil.
[4]Department of Electrical Engineering, University of Taubate, Taubate, Brazil.

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This paper presents a simple approach to model an industrial vibratory bowl feeder. The vibratory feeder is a device used to separate, feed and locate automatically a variety of parts in order to speed up the process of manufacture and assemble in industry. The analytical model obtained is validated through an experimental setup, assembled in laboratory, composed by a capacitive MEMS accelerometer and a data acquisition board all integrated in a LabVIEW application. The accelerometer is composed by an integrated circuit with a capacitive cell and gives an electric signal proportional to the acceleration. This digital signal is integrated twice in order to obtain the level of displacement inside the feeder. Preliminary results show that a good agreement between the experimental and analytical models was achieved.

Key words: Vibratory bowl feeder, vibration, modeling.

INTRODUCTION

Theories of control are being integrated into the industry, motivated by the advances in computational resources. The studies and academic research are providing the creation of several new algorithms, which together with the powerful computational resources are being used to carry out several types of control in several industrial areas. The automatic control systems are found in abundance in industry sectors such as quality control and manufacturing, tool control, space technology, transportation systems, power systems, robots and many others. Within this context, this paper seeks to develop a system of feedback control applied to the control of a vibratory feeder. The vibratory feeders are common in industrial plants with different levels of automation. Besides that feeders are used in separation and automatic positioning of a wide variety of parts optimizing the process of manufacturing and assembly. We have various industrial applications where these machines incorporate partial automation such as centerless grinders, thread cutting machines, thread rolling machines, seamer cover, after all, where there is a need to correctly position parts such as bushings, caps, screws, electronic components, electrical contacts and other. In industrial processes, which are using industrial vibratory feeders, closed loop control systems, are needed in situations where vibration is constant and independent of the amount of rolling stock in your container. Thus, the development of control devices and the use of specific control strategies, using a mathematical viable model are necessary. The knowledge of the behavior of industrial vibratory feeder and its features, as well as the availability of a valid mathematical model, is important to optimize the operation, expanding the possibilities of use and reducing integration costs through the implementation of control systems. In Schroer (1987) the author presents the results of a series of experiments using custom tooled

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*Corresponding author. E-mail: alvaro@unitau.br.

vibratory bowls for presenting non-standard electronic parts to a robot for insertion on printed circuit boards. In Maul and Thomas (1997) the authors developed a mathematical model of a bowl feeder by using state-space methods to evaluate bowl feeder parameters. From the mathematical method, a computer simulation can predict the velocity of the parts in the bowl and subsequently the part feed rate. According to the authors the simulation might be used to improve the design of vibratory bowl feeders. In Jaksic and Maul (2001), the authors described the development of a model of part behavior required for reorienting a part with an air-jet-based computer controlled orienting system. The system can be used to eliminate jamming and improve feed rates in vibratory bowl feeders. The control algorithm described accepts the part's weight, geometry, and its orientation. The authors also used sensors to compare the present with the desired orientation and the algorithm determines the appropriate pulse of air to produce the desired orientation. Ding and Dai (2008) describes a bowl feeder like a platform supported by three prismatic flat-spring, and examines the bowl feeder from the point-of-view of a compliant platform device by applying von Mises' compliance study to each of the flat-spring legs and establishes a screw system of each leg. The compliance and Jacobian matrix of the bowl feeder are presented in their study, the potential and kinetic energies are analyzed, and dynamic models were established, leading to the characteristic equations of the compliant platform device. According to the authors, this generates for the first time the shape function integrated stiffness matrix and inertia matrix. The paper also analyzes the two characteristic equations of both a simplified and a generalized system. They also implement the comparative study of the system natural frequencies between the two system models, and present the stability analysis involving the system hysteresis damping. The effect of platform design parameters on the natural frequencies of the system under damping is identified and modal analysis of the system is carried out according to different forms of the excitation force. The work of Vilán et al. (2009) describes an approximate model for predicting the behavior of a part in a vibratory bowl, following a modification of parameters. The analysis is simplified by using numerical solutions obtained using a simple spreadsheet, which makes the procedure accessible to a wide range of users. The authors present the results in the form of a dynamic simulation using a specific software. In Mucchi et al. (2013) the authors show a linear lumped-parameter model for the prediction of the dynamic behavior of bowl feeders. The model has been experimentally verified by means of modal analyses and operational accelerations. The model parameters, such as the stiffness and damping of rubber mounts, leaf spring stiffness and time-varying excitation, have been experimentally estimated. The proposed model can be used for the analysis of feeder dynamics and for evaluating the effects of changes in design and operational parameters in terms of bowl and base vibration and dynamic forces transmitted to the floor.

This paper presents a simple approach to model an industrial vibratory bowl feeder. The analytical model obtained is validated through an experimental setup, assembled in laboratory composed by a capacitive MEMS accelerometer and a data acquisition board all integrated in a LabVIEW application. The accelerometer is composed by an integrated circuit with a capacitive cell and gives an electric signal proportional to the acceleration. This digital signal is filtered digitally and integrated twice in order to obtain the level of displacement inside the feeder. Preliminary results show that a good agreement between the experimental and analytical models was achieved.

THE VIBRATORY BOWL FEEDER

The vibratory bowl feeder used in this work is shown in Figure 1 and is very similar to the one used by Mucchi et al. (2013). This device can be mechanically analyzed considering its division into two structures: upper and lower.

At the top (Figure 1b), we have a receptacle that receives the material to be moved in sequence to the process in which it is inserted. The receptacle has a base shaped like a disc and is supported by sets of springs, formed by leaf springs straight and arranged in parallel (Figure 1a). These sets of springs have a tilt feature. The spring sets are the elements of support, so one end is fixed at the upper structure, and the opposite end is fixed to the lower structure. The device responsible for moving the structure and producing the vibration is the electromagnetic coil. When it is energized it produces a net force generating an electromagnetic field, which attracts the upper structure that moves back and tilts. In order to validate the model described in the next session, we assembled an experimental setup (Figure 2). The setup is composed by an electronic controller (1), a data acquisition board (2) (*NI MyDAQ from National Instruments, 2 analog inputs (16-bit), 200 kS/s, 2 analog outputs (16 bit), 8 digital IO*), a vibratory bowl feeder (3), a capacitive accelerometer (4) (*MMA6222AEG Freescale Semiconductor, Inc*) and a PC compatible with the software LabVIEW 8.5. installed.

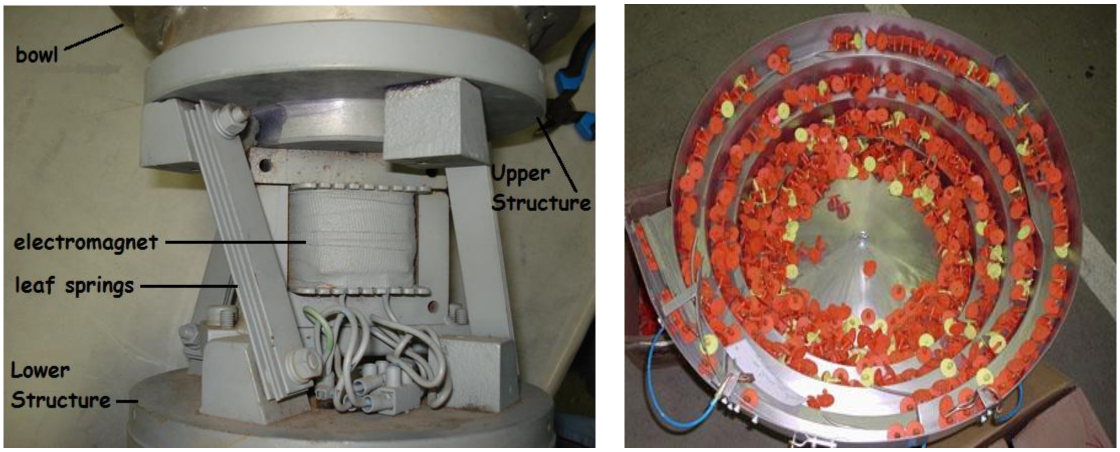
Modeling the vibratory bowl feeder

For construction of a model for the vibratory industrial bowl feeder we initially assumed that the firing of its electromagnetic coil, responsible for the vibration of the bowl is performed through a circuit controlled half-wave rectifier, so with an alternated voltage which is a function of time and varies sinusoidally and can be expressed as Equation (1).

$$V(t) = V_{MAX} \sin(\omega t) \tag{1}$$

In Equation (1), V_{MAX} is the maximum value of the signal amplitude or peak voltage, ω is the angular velocity in radians per second and t is the time in seconds.

The voltage supplied by the electrical net is a sinusoidal alternated voltage. The vibratory industrial bowl feeder is energized with rectified main voltage via a silicon controlled rectifier, a half-wave, based on a SCR (Silicon Controlled Rectifier) thyristor. A diode is an electronic component used in circuits that perform the rectification of the signal. The thyristor SCR is an electronic component that can be controlled by a signal applied to its gate



(a) (b)

Figure 1. (a) The vibratory bowl feeder (b) Top view of the vibratory bowl feeder.

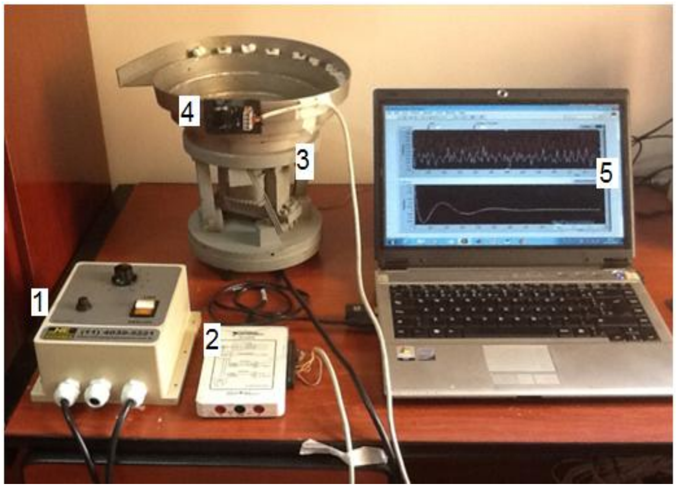


Figure 2. Experimental setup.

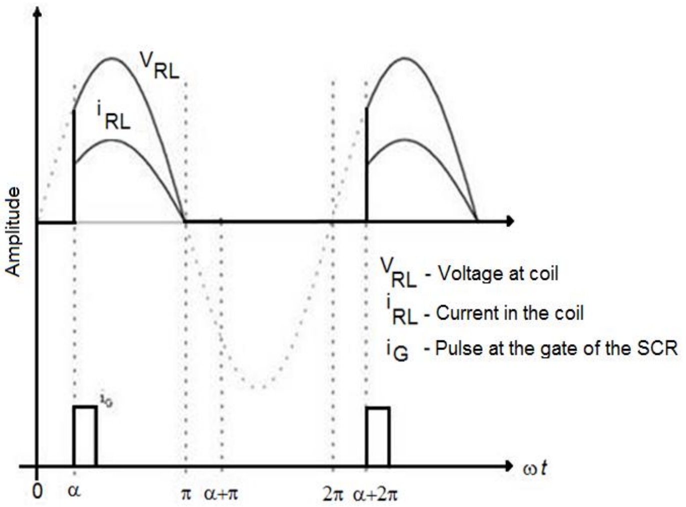


Figure 3. Current and voltage at the coil.

terminal and operates similarly to the diode rectifier. However it only begins to conduct electric current, when a suitable signal is applied to its terminal gate. The time when this pulse is applied to the gate is called the firing angle (α), this time can be represented in degrees, radians or seconds. Figure 3 illustrates that the signal voltage and the electric current begins to be applied to the coil just before the gate pulse is applied to the thyristor. This characteristic enables the thyristor to control the average value of the voltage applied to the load as a function of the firing angle (α). The expression that represents the average value of the voltage applied to the load (V_{DC}), triggered by a SCR is shown in Equation (2).

$$V_{DC} = \frac{1}{T}\int_{\alpha}^{\pi} V_{MAX}\sin(\theta)d\theta \tag{2}$$

In Equation (2), T and θ are the period and the variation angle of the sinusoidal wave respectively. After solving this elementary integral, we can write:

$$V_{DC} = \frac{V_{MAX}}{2\pi}\left[1+\cos(\alpha)\right] \tag{3}$$

Once the electromagnetic coil of the industrial vibratory bowl feeder is driven by half-wave controlled rectifier, in Equation (3) we can see that varying the firing angle, varies the mean value of voltage delivered to the load. The higher the value of the firing angle the lower the power delivered to the coil. The trigger thyristor SCR is performed only on half cycles, half of the period of the AC voltage input ranging from 0 to 180°; this range can be represented in radians from 0 to π or seconds from 0 to 0.00833.

The electrical signal applied to the magnetic coil is periodic with constant frequency of 60 Hz. So the angular velocity of the energy that excites the system is constant and equal to $\omega = 2\times\pi\times60$ or $\omega \approx 377$ rad/s. On the other hand the firing angle is independent of this frequency and can expressed as:

$$\alpha = \omega\, t_G \tag{4}$$

In Equation 4, t_G is the firing time in seconds. Substituting Equation (4) in Equation (3) we reach at:

$$V_{DC} = \frac{V_{MAX}}{2\pi}\left[1+\cos(\omega\, t_G)\right] \tag{5}$$

Table 1. System's physical parameters.

Parameter	Description	Value	Unity
V_{MAX}	Maximum amplitude of the supply voltage	220	V
V_{SMAX}	Maximum amplitude of the accelerometer output voltage	5	V
ω	Angular frequency f = 60Hz	377	rad/s
φ	Phase of the output signal	0	º
S	Accelerometer's Sensibility	23.4	mV/V/g
δ	Constant of Conversion	83.846	mm/s^2

The value of t_G works like an input to the system and establishes the value of V_{DC} which corresponds to the intensity of energy supplied to the bowl feeder. This voltage is proportional to the bowl feeder structure's displacement and also to the vibration of the structure. Once, this vibration will be measured by an accelerometer, we can model the voltage in the accelerometer output as:

$$V_S(t) = A\,V_{DC}\,\sin(\theta + \varphi) \tag{6}$$

In Equation (6), A is the ratio between the maximum value of V_S and V_{MAX}, θ is the angle of the sinusoidal waveform and φ is the phase angle related to the firing angle α. After those considerations we can rewrite the V_S as:

$$V_S(t) = \frac{A}{2\pi} V_{MAX}\,\left(1 + \cos(\omega\, t_G)\right)\sin\left(\omega\left(t + t_D\right)\right) \tag{7}$$

Thus, the bowl feeder acceleration can be modeled as:

$$a(t) = \delta\, V_S(t) \tag{8}$$

In Equation (8), δ is a constant that depends on the sensor sensibility. The accelerometer used in this work has the following characteristics: maximum acceleration 20 g; maximum output voltage 2.5 V; minimum output voltage -2.5 V, offset voltage 2.5 V and supply voltage 5.0 V. Equation (8) can be rewritten as:

$$a(t) = B\sin\left(\omega\left(t + t_D\right)\right) \tag{9}$$

In Equation (9), B is a constant equal to:

$$B = \delta \frac{A}{2\pi} V_{MAX}\,\left(1 + \cos(\omega\, t_G)\right) \tag{10}$$

Integrating Equation (9) we obtain the bowl feeder velocity, in m/s, as:

$$v(t) = -B\,\frac{\cos\left(\omega\left(t + t_D\right)\right)}{\omega} \tag{11}$$

Integrating Equation (11) we obtain:

$$s(t) = -B\,\frac{\sin\left(\omega\left(t + t_D\right)\right)}{\omega^2} \tag{12}$$

Equation (12) represents the displacement of the industrial vibratory bowl feeder, in meters. The drive system is dependent on the constant B which represents the amplitude of the displacement. The argument B is mainly determined by the firing angle of the thyristor SCR which is also dependent on the characteristics of the accelerometer used.

RESULTS AND DISCUSSION

Here we describe the results obtained after we excite the system with a known signal and record the output of the accelerometer. To do so, we used the physical parameter listed in Table 1.

The data in Table 1 was used to calculate the constant B (Equation 10), the bowl feeder' velocity and displacement (Equations (11) and (12)). Before we acquire the accelerometer output signal, we double integrated it, in order to have displacement and compare the experimental displacement with the one obtained by Equation (12). To obtain the results we varied the firing angle ten times from 7.4 ms until 0.05 ms or from 160 to 1°. The results are shown in Table 2. To analyze the results we compare the RMS value of the displacement measured by the accelerometer and the displacement obtained by the Equation (12). In the results we can see that the RMS value of the error is around one millimeter, which shows that the models are very close.

In order to provide a better analysis of the results we also plotted the graphics, shown in Figure 4. Figure 4 shows a graphical comparison between the displacement data. This comparison implies in a model's comparison. As we can see, the comparison between analytical and experimental models, show a phase angle, which is coherent, once there is a lack of time between the excitation and the measuring processes. Once again we can see that the models (analytical and experimental) are very close, which validates the analytical model developed in this work.

In this paper we present a simple and effective approach to model an industrial vibratory bowl feeder. The analytical model obtained is validated through an experimental setup, assembled in laboratory composed by a capacitive MEMS accelerometer and a data acquisition board all integrated in a LabVIEW application. The accelerometer, composed by an integrated circuit with a capacitive cell, gives an electric signal proportional

Table 2. Numerical results.

Case#	t_G (ms)	α (°)	Displacement's RMS value (mm)		Error RMS (mm)
			Experimental	Analytics	
1	7.40	160	0.0211	0.0201	0.028631
2	6.85	148	0.0576	0.0506	0.099583
3	6.11	132	0.1270	0.1100	0.082819
4	4.40	95	0.3544	0.3032	0.654314
5	3.15	58	0.5899	0.4564	0.232604
6	1.39	30	0.7455	0.6195	1.165514
7	0.37	8	0.8002	0.6607	0.140789
8	0.23	5	0.8512	0.6626	1.343547
9	0.14	3	0.8683	0.6635	1.525945
10	0.05	1	0.8628	0.6639	0.235918

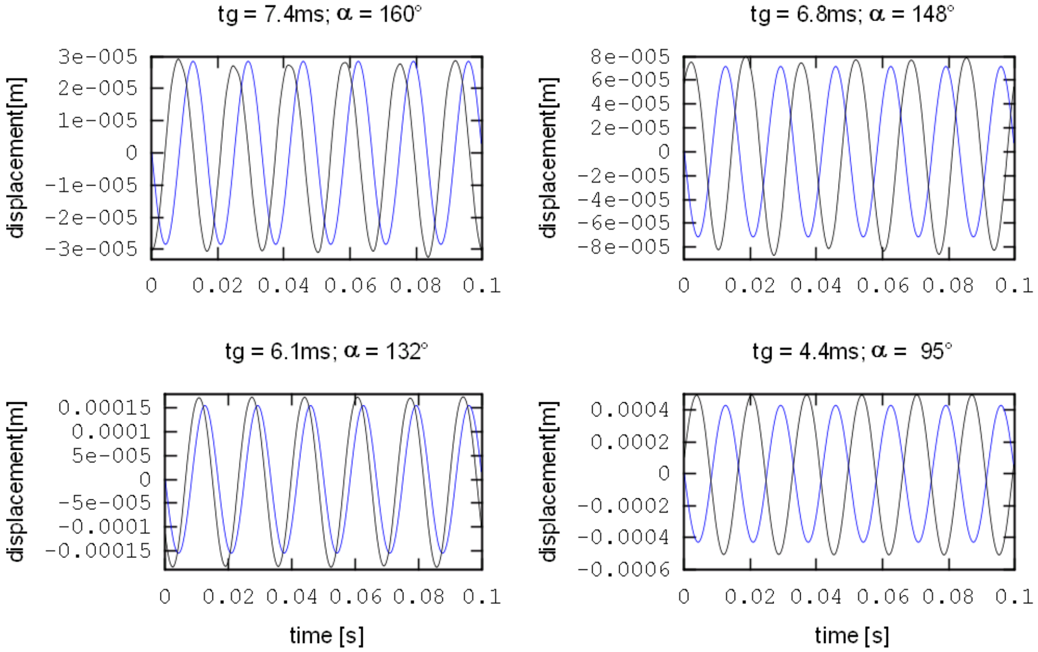


Figure 4. Comparison between analytical and experimental data.

to the acceleration. This digital signal is filtered digitally and integrated twice in order to obtain the level of displacement inside the feeder. The results show a good agreement between the analytical and experimental data with an error RMS about 1 mm. The work is in progress and with the model validation we intend, as further work, to use it to implement classical control techniques in order to keep the bowl feeder displacement inside a desirable range.

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