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Oscillator analogy for modelling the manufacturing systems dynamics

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3 The purpose of this paper is to present an approach of modelling and analysis of the
4 dynamic behaviour of manufacturing systems. The manufacturing system is considered
5 to be responding to an excitation, namely a demand that varies over time, by producing a
6 number of parts over time. This resembles a mechanical system that displaces its mass
7 responding to a varying input force. Based on this analogy, this paper establishes a
8 manufacturing system's modelling method. A system identification technique is used for
9 deriving inertia, damping and stiffness from the manufacturing system's response to
10 different excitations. Based on these attributes, the response of a manufacturing system
11 to any given input can be estimated. Furthermore, a definition for assessing
12 manufacturing flexibility, based on this approach, is being discussed.
13

14 *Keywords:* manufacturing systems, modelling, flexibility
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16 **1. Introduction**

17
18 A manufacturing system can be defined as *a combination of humans, machinery and*
19 *equipment that are bound by a common material and information flow.* Raw materials
20 and energy are the input to a manufacturing system. Information is also input to a
21 manufacturing system, in the form of customer demand for the system's products. The
22 outputs of a manufacturing system can likewise be divided into materials, such as
23 finished goods and scrap, and information, such as measures of system performance
24 (Chryssolouris (2005)). Manufacturing systems are large and complex, having many
25 interacting components, exhibiting strong dynamic behaviour.
26

27 Mathematical programming, dynamic programming optimization techniques and
28 the queuing theory have been widely used over the past years as modelling and analysis
29 tools for studying the behaviour of production systems (Chryssolouris (2005)). In Edghill
30 and Towill (1990) the frequency response of a manufacturing system has been proposed,
31 as a general-purpose model of manufacturing systems, and the way it can be used to
32 measure the system's performance to targeted objectives, has been demonstrated. A
33 dynamical approach for modelling and control of production systems, based on the
34 Nonlinear Dynamics Theory as well as a method to regulate the work in progress levels
35 via nonlinear control mechanisms, was demonstrated in Scholz-Reiter *et al.* (2002). In a
36 similar manner, an application of the chaos theory to manufacturing systems was
37 presented in Chryssolouris *et al.* (2004) in which it was demonstrated how the concepts
38 related to the chaos theory could reveal interesting patterns, associated with the
39 scheduling problem in manufacturing systems. In Wiendahl (1995), Wiendahl and
40 Breithaupt (1999) the funnel analogy has been used to explain a method that determines
41 throughput times on a shop floor by controlling the amount of jobs released and, thus, the
42 input to the production system. In a similar manner, Breithaupt (2000) developed
43 methods based on the control theory for planning the production in a complete job-shop.
44 Discrete Event Simulation (DES) has also been widely used as a means to design new
45 manufacturing systems or to improve existing ones (Law and McComas (1998), Jägstam
46 and Klingstam (2002)). A comparison of DES modelling and continuous models, based
47 on system dynamics, was described in Baines and Harrison (1999). In their work, they
48 argued that DES modelling seemed to give more credible models due to the level of detail
49 that could be included in such models, but the models based on system dynamics needed
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less time to be built and this could be advantageous in strategic issues, within a manufacturing industry. Other methods of modelling manufacturing systems include the biological manufacturing systems (Ueda (1998)), the fractal company concept (Shin and Rist (1998)), and neural networks (Chryssolouris *et al.* (1990)). Furthermore analogies between manufacturing and concepts in physics, such as turbulent flow (Wiendahl *et al.* (2002a), Wiendahl *et al.* (2002b)) and transport phenomena for production networks and supply chains (Scholz-Reiter *et al.* (2006)) have been also presented in the past. A list of methods applied to different classes of manufacturing systems design problems was presented in Ueda *et al.* (2001).

In Chryssolouris *et al.* (1998) they have used the mechanical analogy concept to assess the flexibility of a manufacturing system. Their approach calculates the damping factor of a manufacturing system, from the eigenvalues of the transfer function in the frequency domain. However, they focused on presenting a method of evaluating flexibility in manufacturing systems, motivated by the idea that the *damping factor* of a mechanical system defines its ability to respond to a varying input. They did not focus on studying, in more detail, how the analogy concept could be used for modelling manufacturing systems, in general. The purpose of this work is to explore a new way of analyzing and modelling manufacturing (MFG) systems by describing the behaviour of an MFG system with the attributes of a mechanical (MECH) system -namely its inertia, damping and stiffness.

2. The analogy between MECH and MFG system

A single degree of freedom mass vibrator and a production system (figure 1) have been considered simultaneously: MFG systems have as excitation a 'demand', typically expressed in quantities of products that are due at a particular time and as output the delivery of these products or in other words, the system's response over time. The orders that constitute the demand on the system may satisfy the needs of particular customers (make-to-order-production) or they may go to the inventory of the company (make-to-inventory-production). Due dates of the orders may be set by the customers or may be determined by the company in order for seasonal demands and other market driven factors to be accommodated. Since both demand and production vary over time, an MFG system exhibits a dynamic behaviour. The single degree of freedom spring, mass, damper vibrator oscillates responding to input, typically a force varying over time, while the displacement of the mass is considered to be the system's output. The behaviour of this simple MECH system is well known and easy to analyse. Although it is rather simple, it could provide useful insight into the analogy of an MFG to a MECH system.

[Insert figure 1 about here]

3. System identification

The identification of the mechanical attributes, namely mass m , damper c and stiffness k from the impulse response of the MFG system, can be accomplished in the following two steps:

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1. Record the impulse response $y(t)$ (where t is the time index, $t \in [0,1,\dots,T-1]$, the impulse response values $y(t)$ are recorded per sampling interval $\Delta t = 1$ TimeUnit (TU) and T is the number of recorded response values) of the MFG system. The impulse response $y(t)$ of an MFG system may be the number of parts delivered in each period t by the MFG system. The impulse response is the output of a system when an impulse is applied to the system. Impulse is the time integral of a suddenly applied non-periodic excitation $F(t)$, and is designated by the notation \hat{F} :

$$\hat{F} = \int F(t)dt$$

The impulse in an MFG system may be a Number (N_0) of parts requested to be processed by the system at time $t=0$.

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2. Assuming that the impulse response has been generated by a single degree of freedom MECH system, identify the m , c and k attributes from the response. The response/displacement $x(t)$ of a single degree of freedom damper, spring, mass vibrator under impulse excitation (see the appendix) can be derived from the differential equation that describes the motion of the simple MECH system after the impulse excitation \hat{F} at time $t = 0$ is:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = \hat{F} \quad (1)$$

Where:

m is the mass coefficient

c is the damper coefficient

k is the stiffness coefficient

$x(t)$ is the displacement of the MECH system

$\dot{x}(t)$ is the velocity of the MECH system

$\ddot{x}(t)$ is the acceleration of the MECH system

In order for the m , c , k attributes of the system's impulse response to be identified, the state-space representation of the single degree of freedom MECH system is used (Meirovitch (2001)). Equation (1) can be rewritten in the following form:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\hat{F} \quad (2)$$

Where:

$$\mathbf{x}(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} \text{ and } x_1(t) = x(t), x_2(t) = \dot{x}(t), \mathbf{A} = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{c}{m} \end{bmatrix} \text{ and } \mathbf{B} = \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix}$$

When a \hat{F} impulse is applied at $t=0^+$ the initial velocity is given by equation:

$$\dot{x}(0^+) = \frac{\hat{F}}{m} \quad (3)$$

The initial velocity can be directly estimated by the first values of the recorded response $x(t)$; consequently m is directly estimated from the response. By fitting the state space model to the impulse response data, parameters c , k can be approximated. The parameters of \mathbf{A} are computed numerically by iterative search methods (Ljung (1999), Matlab System Identification Toolbox / Matlab (2006)).

The proposed identification method finds the m , c , k values that can approximate the MFG impulse response $y(t)$. The fit of the model's output ($x(t)$) to the original response data ($y(t)$) can also be calculated:

$$fit = 100 \times \left(1 - \frac{\sqrt{\sum_{t=0}^{T-1} (x(t) - y(t))^2}}{\sqrt{\sum_{t=0}^{T-1} (y(t) - Y)^2}} \right) \quad (4)$$

Where:

fit measures the accuracy of the approximation. The closer the fit is to 100 the better the accuracy of the approximation.

T is the number of the sampled impulse response values

t is the time index and $t \in [0, 1, \dots, T-1]$

$y(t)$ is the impulse response of the MFG system at time t

$x(t)$ is the response of the MECH model (i.e. the MECH system having the estimated m , c , k attributes)

Y is the average value of the MFG impulse response

The identification approach described above can be applied to the case that data on input, such as demand of parts over time, and output, such as number of parts delivered over time, are recorded. Such data are usually available in modern ERP systems for different time scales, such as daily, weekly, monthly, annually etc.

4. Manufacturing system

In order to describe the behaviour of an MFG system, the assumption has been made that the Production Rate (PR) of the system depends on the number of parts waiting to be processed. This is an assumption that tends to be realistic for a series of industrial sectors. Particularly, the order-to-delivery lead time plays a prominent role in determining the production rate as the producer attempts satisfy demand. A research in UK, related to automotive products, has shown that the 61% of the customers want their vehicle to be delivered within 14 days (Elias, 2002) and (Holweg et al. 2005). North American consumers would wait no longer than 3 weeks for their car, even if it is custom-built (Holweg and Pil, 2004) and (Holweg et al. 2005). It is, therefore, important for manufacturing systems to follow the demand by adjusting their production rate. In our approach, the desired PR at each time t is given by equation (5):

$$PR_t = \frac{N_t}{D} \quad (5)$$

Where:

N_t is the Number of parts waiting to be processed at time t

PR_t is the Production Rate expressed in parts/TU at time t that the system operates on

D describes the delivery time for N_t parts to be produced when the system works on production rate PR_t . It is measured in TU (e.g. days, weeks etc) and $D \geq 1$.

The interpretation of equation (5) is that: the more parts are in the queue of the system the more the system tends to increase its PR so as to compensate for long waiting and delivery times. If the queue decreases below a certain level then PR should also be

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decreased. Other research work has also assumed that production rate has a linear relationship with demand and indirectly with parts or products waiting to be processed. The production rate has to increase as demand increases and, similarly, as demand slows down the production rate needs to decrease (Sadjadi *et al.* (2005)).

There is usually a delay in increasing PR, though. For this reason, we have introduced factor $C_1 \in [0,1]$ that influences the value of PR: C_1 defines the percentage of the desired increase in the PR that can be practically achieved within a time period. For example if the desired increase of the PR is 200 parts/TU in one period and $C_1=10\%$, then the achievable increase, within a period, can only be 20 parts/TU. We assume that C_1 is constant and does not change over time. Moreover, we assume that the manufacturing system should never become idle. Stated otherwise, the PR of the system should be zero when the number of parts in the queue is also zero. Thus, the PR of the system should decrease in order to satisfy the above assumption. The decrease of PR depends on factor $C_2 \in [0,1]$. C_2 defines the percentage of the desired decrease in PR that can be actually achieved within a time period. The decrease is towards PR=0. We assume that C_2 remains constant over time. Consequently, the PR of the system, at any given time t , is given by the following equations:

$$PR_t = (N_t / D - PR_{t-1}) \cdot C_1 + PR_{t-1}, \text{ when PR should be increased} \quad (6)$$

$$PR_t = N_t / D, \text{ (e.g. the system operates on its maximum desired capacity).} \quad (7)$$

$$PR_t = (1 - C_2) \cdot PR_{t-1}, \text{ when PR should be decreased} \quad (8)$$

In figure 2, a typical graph of PR is presented if we excite the system having $D=40$, $C_1=0.08$ and $C_2=0.1$, with an impulse demand $N_0=10\ 000$ parts at $t=0$. The graph of figure 2 has been acquired via simulation and the use of equations (6), (7), (8). The PR at each time period t , determines the number of parts produced by the production system at t . Thus, the response of the MFG system is $y(t)=PR_t \forall t \in [0,1,\dots,T-1]$.

[Insert figure 2 about here]

5. m , c , k as characteristics of the manufacturing system

If the characteristics D , C_1 , C_2 of the MFG system do not change, then the calculated m , c , k from the impulse response of the MFG system remain practically the same, whilst the applied impulses may change considerably. We have assumed 20 different MFG systems as shown in table 1. Parameters D , C_1 , C_2 , in table 1, have been randomly generated within defined limits ($D \in [20, 50]$, $C_1 \in [0.01, 0.1]$ and $C_2 \in [0.05, 0.15]$). Five different impulses have been applied to each system. The magnitude (N_0) of the impulses is: 1000, 2000, 5000, 10 000 and 15 000 parts. Thus, in total, 100 simulation runs took place. In each simulation, each system's impulse response has been recorded for a number of T periods. The value of T depends both on the system parameters and the magnitude of the impulse. Then, by using the identification method described in

paragraph 3 and the recorded impulse response, the system's m , c , k attributes are calculated. The results of each system are presented in table 2.

[Insert table 1 and table 2 about here]

The results in table 2 indicate that m , c , k can be considered as characteristics of the MFG system, since their value does not change for different magnitudes of the applied impulse. This is evident from the low value of the standard deviation for all m , c , k . More specifically, considering the results in table 2, it is observed that the calculated mass remains totally unchanged (has zero standard deviation in all systems). This occurs because m is calculated directly from the initial velocity as defined in equation (3). The initial velocity is approximated by the response of the system during the first recording period according to (6). Thus, m is calculated as follows:

$$PR_0 = (N_0/D) \cdot C_1 \Rightarrow \dot{x}(0^+) = (N_0/D) \cdot C_1 \Rightarrow m = D/C_1 \quad (9)$$

Where:

PR_0 is the Production Rate at $t=0$

N_0 is the magnitude of the impulse applied at $t=0$.

$\dot{x}(0^+)$ is the initial velocity

6. Estimating the response of the manufacturing system

Once the m , c , k attributes of the MFG system have been identified from the impulse response, they can be used for *estimating the response of the MFG system under a different input excitation* without having to execute rather complex simulation by using the system's actual parameters.

In order to present the prediction capabilities of the modelling approach, a system with $D=2$, $C_1=0.05$ and $C_2=0.1$ has been used as an example. The calculated MECH parameters are: $m=40$, $c=11.597$, $k=1.1358$ with $\text{fit}=73.2\%$. In this MFG system, input for 1000 TU has been applied. The input demand is generated by a normal distribution with Mean Value=100 parts and Standard Deviation=20 parts (see figure 3). The response of the MFG system for 1000 TU is given in figure 4 and it is calculated via simulation and equations (6), (7), (8). The response of the corresponding MECH system by applying the same input force is given in figure 5. The correlation coefficient between the MFG (figure 4) and MECH (figure 5) system response is 0.68. As it is shown in figure 4, there is a lot of fluctuation (sudden drop and increase) in the response of the MFG system. If the response of the MFG system is smoothed with the use of the *moving average* method, then the response becomes as shown in figure 6. The moving average method has been applied with a time span of 5 TU and consequently, the smoothed response of the MFG system, shown in figure 6, is given by equation:

$$y_s(t) = \frac{1}{5} \sum_{i=t}^{t+5} (y(i)), \quad (10)$$

Where:

$t \in [0, 1, \dots, T-1]$ and T is number of recorded response values

$y_s(t)$ is the smoothed response

$y(i)$ is the response of the MFG system without any smoothing

The correlation coefficient between the smoothed manufacturing response $y_s(t)$ and the corresponding MECH response $x(t)$ is 0.93. Consequently, if the MFG system's m , c , k attributes are known, its response to any given input can be directly calculated, with a good approximation by applying the same input to the MECH counterpart.

[Insert figure 3, figure 4, figure 5 and figure 6 about here]

7. Defining flexibility in a MFG system using the analogy

Based on the modelling of MFG systems in paragraph 4, the system's flexibility is proportional to its parameter C_1 :

$$\text{flexibility} = f(C_1) \quad (11)$$

In the discussion of the appendix, it has been presented that the time, required for a mechanical system to reach its first peak after an initial excitation is applied, can be

defined as a function of m , c and k in the following manner $f\left(\frac{k}{m \cdot c}\right)$. In a similar

manner, since flexibility in an MFG system is considered the ability to quickly increase its production rate and respond to changes in the demand, it is expected that flexibility in an MFG system will also be proportional to m , c and k , in the same way as it is the time required by the MECH system to reach its first peak. Thus, we can define flexibility by using the m , c and k attributes in the following manner:

$$\text{flexibility} = f\left(\frac{k}{m \cdot c}\right) \quad (12)$$

Equation (12) defines a hypothesis based rather on qualitative assessments than on quantitative ones. Thus, in the paragraphs below, we show that equation (12) can be validated through numerical experiments.

The proportionality to $(1/m)$ can be directly shown by equation (9):

$$m = D/C_1 \Rightarrow C_1 = D/m \Rightarrow C_1 = f(1/m) \quad (13)$$

The relation between C_1 and k is

$$C_1 = f(k) \quad (14)$$

This is shown by plotting C_1 against k in figure 7. The points in figure 7 have been generated by finding attribute k after the execution of 50 simulation experiments with $D=30$ and $C_2=0.15$, $N_0=5000$ and C_1 varying in $[0.05, 0.15]$. In each experiment, the m , c , k parameters have been identified. In order to avoid the bias of C_1 with m (as shown in equation (13)) we assume that in each of the 50 experiments m is calculated by equation

$$m = A/C_0 \quad (15)$$

Where:

C_0 is the value of C_1 at the first recording period and it is the same for all 50 systems (and $C_0=0.10$).

1
2 The plot of figure 7 shows that the assumption of equation (14) is valid.

3
4 [Insert figure 7 about here]

5
6 The relation between C_1 and c is:

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$$C_1 = f(1/c) \tag{16}$$

9
10 The validation for equation (16) derives from the same simulation experiments as in the
11 case of equation (14). The results are presented in figure 8 and indicate that the
12 assumption of equation (16) is valid as well.

13
14 [Insert figure 8 about here]

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16 Combining equations (12), (13), (14) and (16) it becomes that:

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18
$$C_1 = f\left(\frac{k}{m \cdot c}\right) \tag{17}$$

19
20 Consequently, from equations (11) and (17) it is clear that equation (12) is a proper way
21 of defining flexibility in an MFG system.

22
23 Further to the above analysis, in figure 9, the plot of equation (17) is presented for
24 the same 50 experiments. The plot in figure 9 validates, in an aggregated manner, the
25 assumption of equations (12) and (17).

26
27 [Insert figure 9 about here]

28
29 The flexibility definition of equation (12) can be used in order for the flexibility of
30 different manufacturing systems to be estimated when m , c , k attributes have been
31 identified. The main benefit of such a measure is that complex details regarding the
32 individual components of an MFG system (machines, conveyors etc) are abstracted and
33 an overall picture regarding flexibility can be achieved. Moreover, the definition of
34 equation (12) is generic since it can be applied to any level of a machine, a department, a
35 shop-floor, a factory etc.

36 **8. Conclusions and future work**

37
38 In this paper, an analogy between the dynamic behaviour of a simple mechanical system
39 and a more complex manufacturing system is drawn. The identification of the MECH
40 attributes from the impulse response of the MFG system can be achieved by using the
41 system's identification techniques. Based on the identification of the mechanical
42 attributes, it is shown that the future output of the MFG system can be estimated.
43 Additionally, a new modelling approach of manufacturing flexibility has been introduced
44 with the use of mechanical attributes.

45
46 This work is a first step in the definition of a complete method that could use the
47 mechanical analogy concept to design and study MFG systems. It is not expected that a
48 simple MECH system can be used to simulate all the complexity existing in an MFG
49 system. Future research will seek for more sophisticated mechanical models (more
50 masses, springs etc. connected in different ways) expected to better simulate a more

complex MFG behaviour. Other models may also be considered and explored for representing the relationship between production rate and demand or products / parts waiting to be processed. Additional investigation is needed to show that the suggested flexibility modelling can be used for comparing the flexibility among different manufacturing systems under several demand excitations. Finally, further research has to be done towards modelling other characteristics of a manufacturing system, such as throughput or capacity.

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Appendix A

The response (displacement) of a damped single degree of freedom mechanical system to an impulse excitation at time $t = 0$ is deduced by equation (A.1) (Thomson (1993)):

$$x(t) = \frac{\hat{F}}{m\omega_n \sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \sin \sqrt{1-\zeta^2} \omega_n t \quad (\text{A.1})$$

Where:

$$\omega_n = \sqrt{\frac{k}{m}}, \quad \zeta = \frac{c}{2m\omega_n}$$

m is the mass, c is the damper, k is the stiffness and $x(t)$ is the displacement.

A typical oscillation of a single degree of freedom MECH system when excited by an impulse is shown in figure 10.

[Insert figure 10 about here]

From equation (A.1) we draw the following conclusions regarding the response of the system related to the changes of k , c and m :

- The bigger the stiffness k of the system is, the sooner the system's oscillation reaches its first peak and the smaller that peak is.
- The bigger the damping c of the system is, the later on the system's oscillation reaches its first peak and the smaller that peak is.
- The bigger the mass m of the system is, the later on the system's oscillation reaches its first peak and the smaller that peak is.

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Tables

Table 1: Systems used to verify that k, m, c can be considered as system's characteristics.

System	<i>D</i>	<i>C</i> ₁	<i>C</i> ₂
1	47.95	0.04	0.12
2	31.76	0.07	0.12
3	31.92	0.05	0.12
4	45.13	0.04	0.09
5	37.84	0.06	0.12
6	35.34	0.08	0.10
7	25.58	0.07	0.15
8	44.20	0.07	0.10
9	23.44	0.07	0.09
10	24.20	0.06	0.13
11	40.22	0.10	0.15
12	21.77	0.04	0.10
13	27.85	0.06	0.05
14	37.13	0.07	0.15
15	42.52	0.08	0.09
16	39.03	0.08	0.06
17	48.36	0.09	0.11
18	27.61	0.09	0.10
19	41.98	0.05	0.15
20	22.16	0.06	0.08

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Table 2: Results indicating that k, c, m could be considered as characteristics of the system

System	m		c		k		Average fit (%)
	Mean Value	Standard Dev.	Mean Value	Standard Dev.	Mean Value	Standard Dev.	
1	1193.7	0	35.839	1.3076	1.1343	0.0173	70.6
2	477.85	0	26.269	0.8516	1.0845	0.0115	76.3
3	675.8	0	27.476	1.5723	1.1516	0.0220	74.2
4	1038.7	0	36.583	1.4159	1.1040	0.0156	74.3
5	621.18	0	29.584	0.8644	1.0775	0.0123	73.7
6	442.43	0	28.711	0.3942	1.0311	0.0040	78.2
7	350.1	0	21.418	0.8770	1.1102	0.0152	75.9
8	602.82	0	34.117	0.3575	1.0103	0.0040	73.6
9	335.62	0	23.94	0.2211	1.1111	0.0039	81.3
10	396.68	0	22.027	1.1582	1.1434	0.0181	75.6
11	402.38	0	29.866	0.2258	0.9800	0.0040	64.9
12	513.01	0	24.4	1.3544	1.1993	0.0138	71.7
13	436.84	0	30.472	0.4970	1.1024	0.0069	84.8
14	508.12	0	27.859	0.4264	1.0526	0.0078	69.4
15	555.04	0	33.122	0.3492	1.0089	0.0036	74.8
16	474.38	0	33.786	0.2189	1.0211	0.0046	86.3
17	523.22	0	36.063	0.1751	0.9593	0.0027	66.4
18	311.55	0	23.904	0.2834	1.0530	0.0022	81.8
19	874.57	0	30.626	0.8102	1.1325	0.0138	68.6
20	370.56	0	24.904	0.3010	1.1423	0.0082	79.0

Figures list

Figure 1: The Mechanical System and the Manufacturing System

Figure 2: A typical response of the simple manufacturing system when an impulse is applied upon it.

Figure 3: Input applied to the manufacturing system

Figure 4: Response of the manufacturing system

Figure 5: Response of the mechanical analogy system

Figure 6: Smoothed response of the manufacturing system.

Figure 7: Analogy between C_1 and k

Figure 8: Analogy between C_1 and $1/c$

Figure 9: Analogy between C_1 and $k/(mc)$

Figure 10: Transient response of a single degree of freedom MECH system after an impulse excitation.

Figures

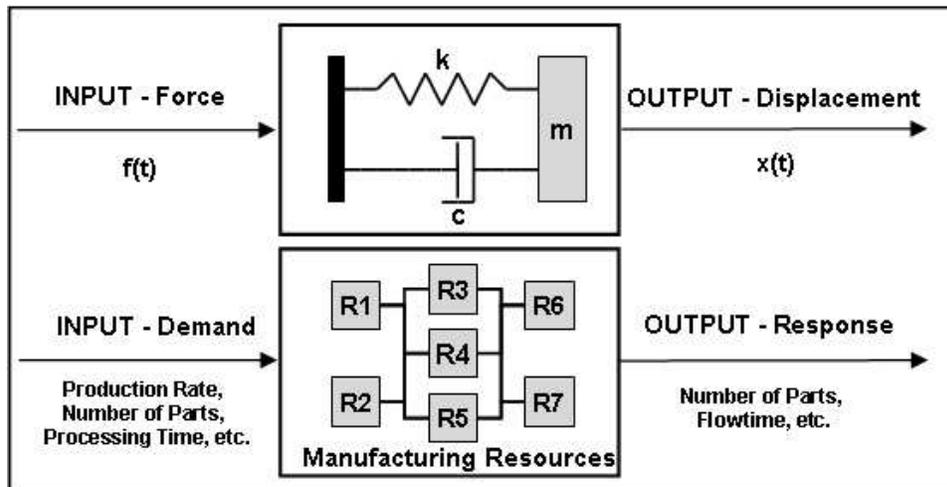


Figure 1: The Mechanical System and the Manufacturing System

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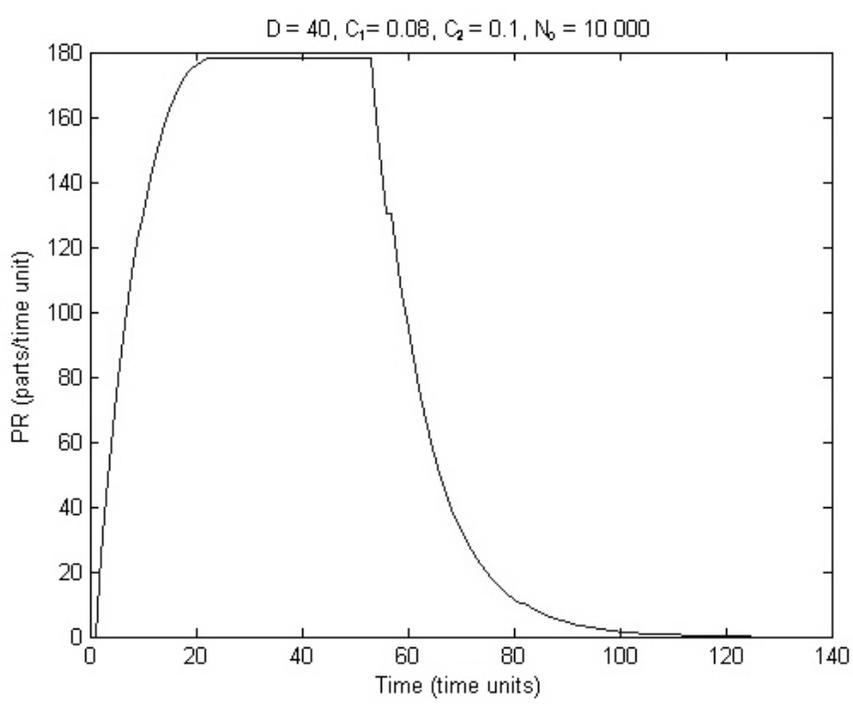


Figure 2: A typical response of the simple manufacturing system when an impulse is applied upon it.

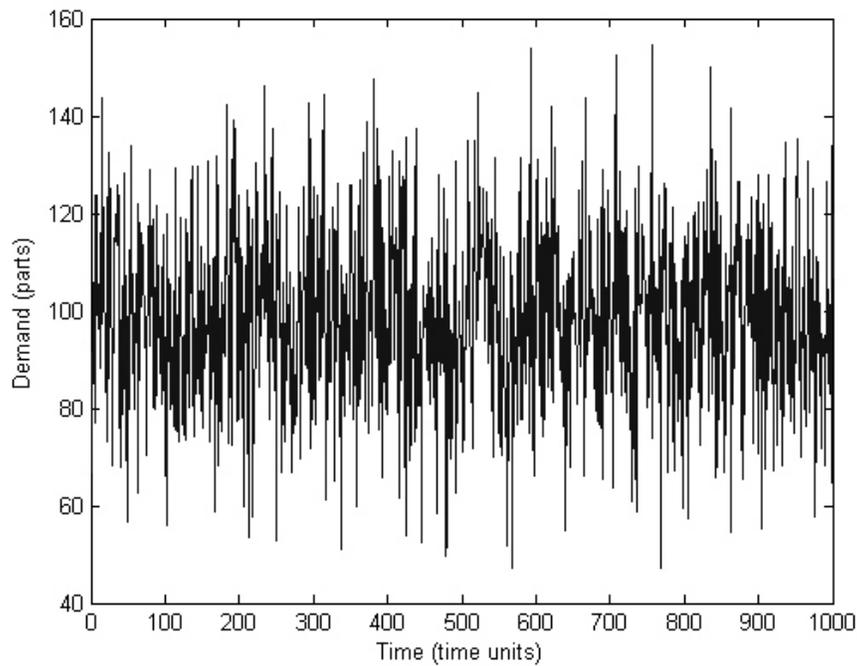


Figure 3: Input applied to the manufacturing system

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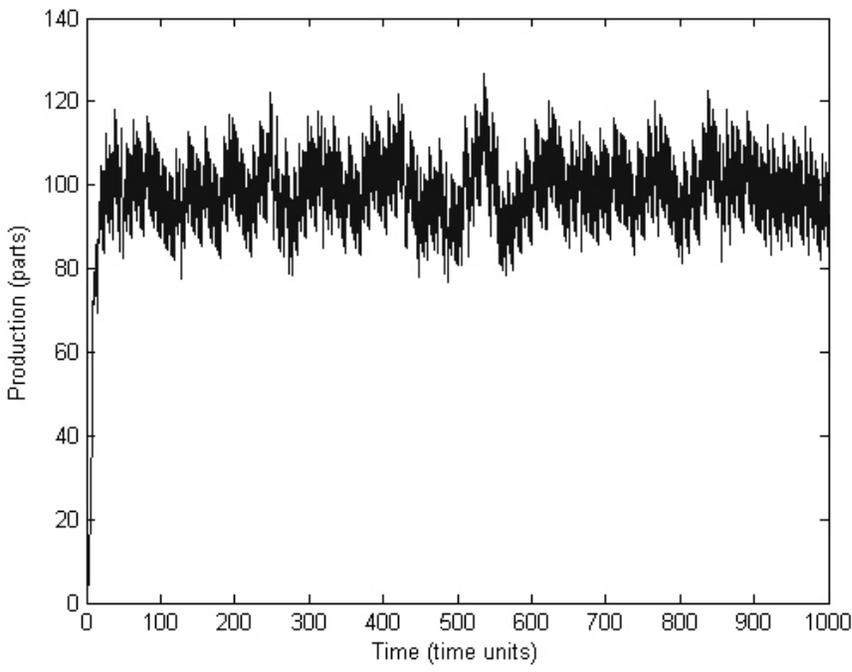


Figure 4: Response of the manufacturing system

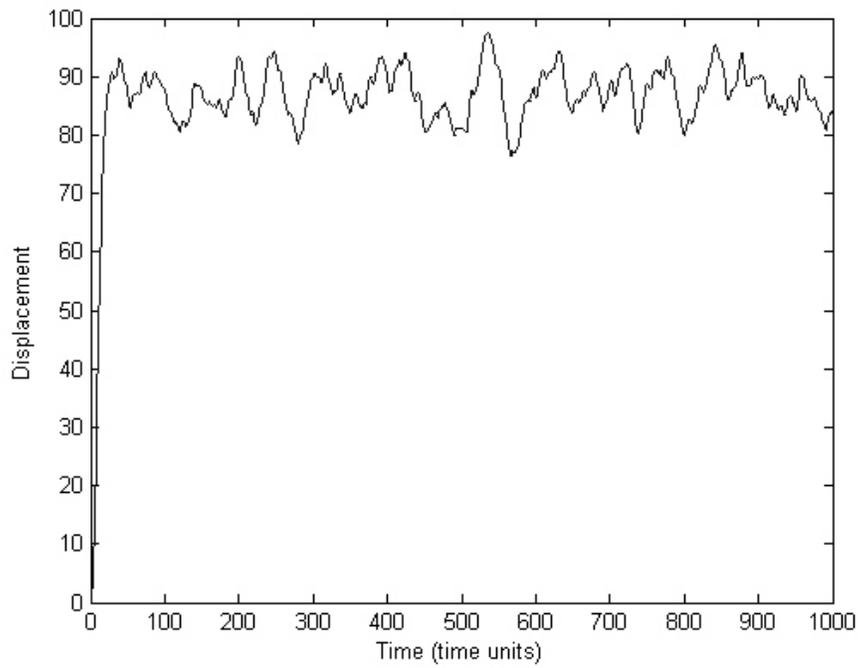


Figure 5: Response of the mechanical analogy system

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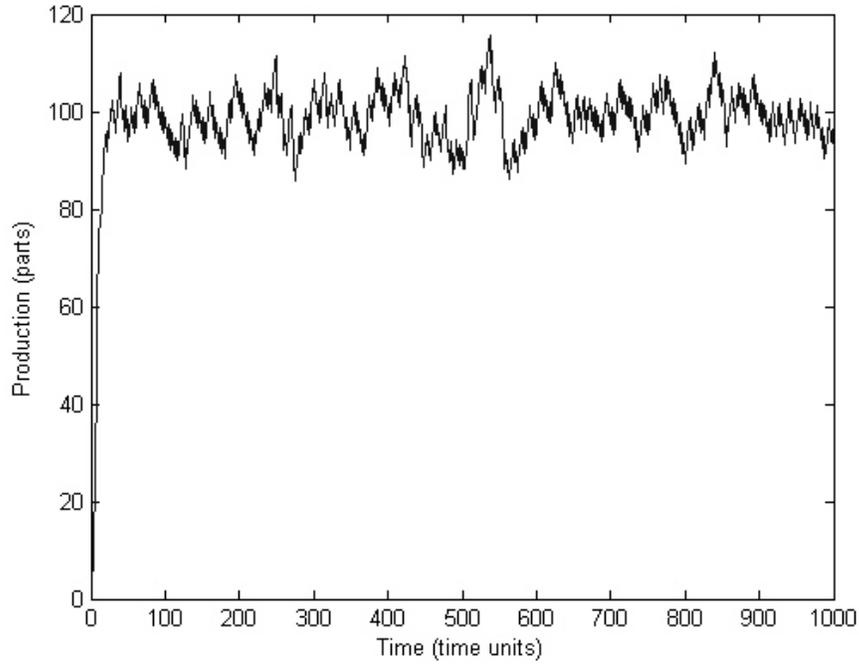


Figure 6: Smoothed response of the manufacturing system.

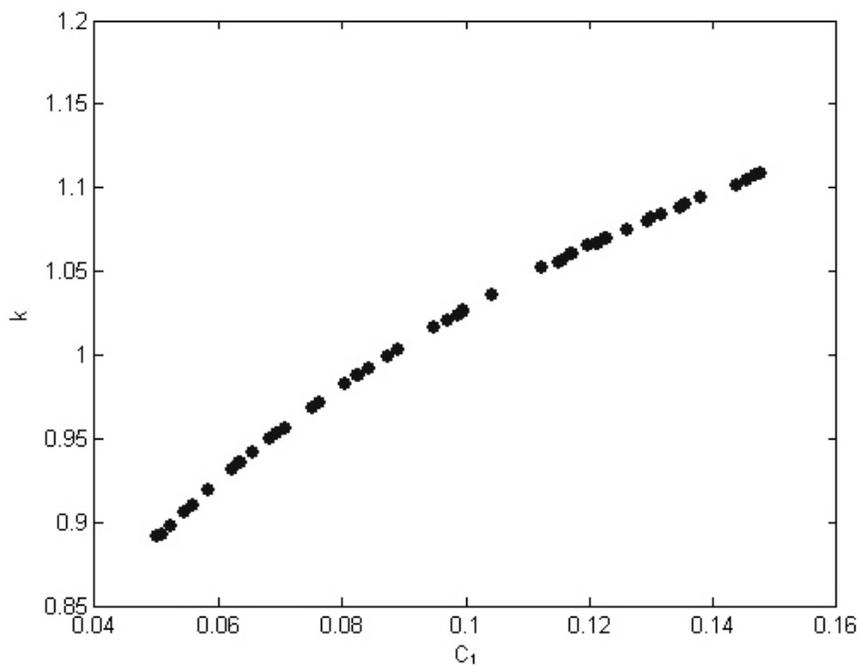


Figure 7: Analogy between C_1 and k

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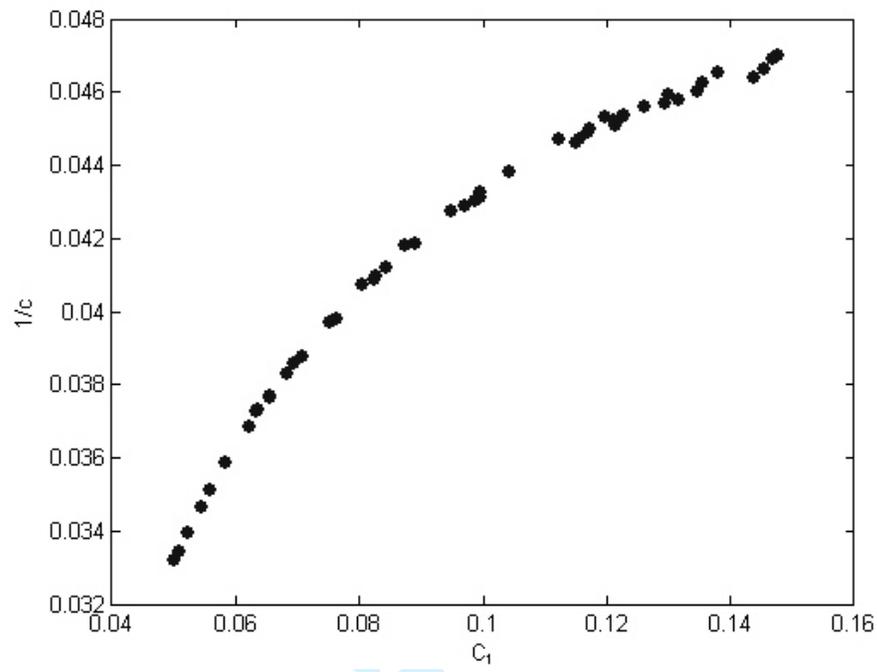


Figure 8: Analogy between C_1 and $1/c$

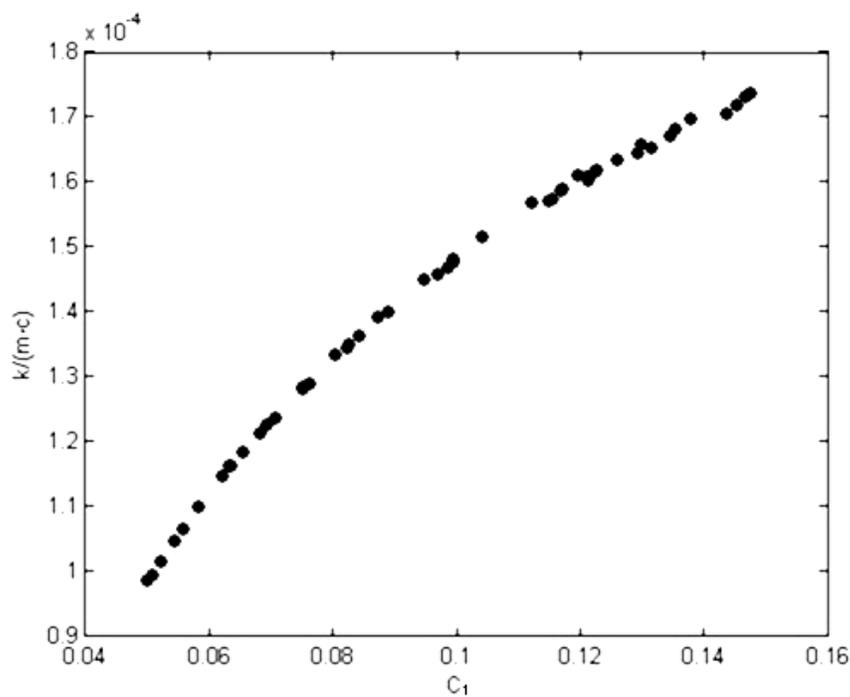


Figure 9: Analogy between C_1 and $k/(m \cdot c)$

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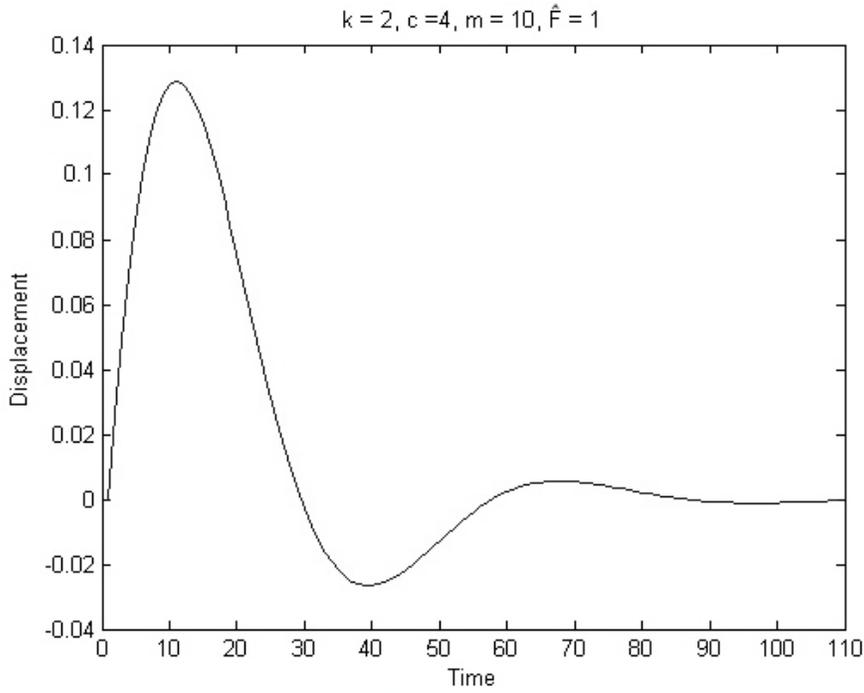


Figure 10: Transient response of a single degree of freedom MECH system after an impulse excitation.