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Transient Response of Damped Beat-Up Mechanism for Narrow Looms

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Abstract: The influence of damping element on the parametric instability of a narrow loom beat-up mechanism is investigated. The mechanism is modeled as a SDOF Second-Order differential equation. The model is subjected to two forcing functions; the turning effect of the driving shaft and the resulting impact on the system due to the beat-up action of the beater. In this study, the function for describing the input forcing functions on SDOF beater system is an arbitrary one and the transient response is expressed as a functional relation with time using Laplace transform. The complete solutions for the transient response are developed for five cases of the damping coefficient. A range of parameters for the damping coefficient required to stabilize the system was obtained.

Key words: Beat-up, mechanism, stability, response, impulsive, systems, torque

INTRODUCTION

The stability of a system relates to its response to inputs and other disturbances from its surrounding. A system which remains in a constant state unless affected by an external action and which returns to a constant state when the external action is removed can be considered to be stable. The stability of a system is important and is generally a safety issue requiring concern in engineering system. It is often desired to understand the extent of system stability in order to be able to determine its degree of performance.

The beat-up mechanism of a narrow loom is a substructure of the narrow loom mechanism which generates a DRRD harmonic motion for beating the weft into the yarn during weaving process as reported in Raji (2000). The beater mechanism is subjected to impact excitation resulting from its beat-up action during its operation and the system experiences instability as a result of discontinuity in its velocity as discussed in an earlier study under review; the impulse-momentum technique was used to expose the instability experienced in the system. The instability of the mechanism could cause the system's failure which in turn will affect the output of the weave. The need therefore arise to introduce a control element into the system to solve this problem of instability.

Improving the stability of systems has been a subject of discuss for long now. Michel and Hu (2000) and Haddad and Nersesov (2004) developed vector Lyapunov theory used for analyzing system stability, the vector Lyapunov function was introduced as a generalization of control Lyapunov functions to show that asymptotic stability of a non-linear dynamic system is equivalent to the existence of a control vector Lapunov function. A numerical decentralized feedback control law was developed to decentralized non-linear dynamical system in-order to obtain generalized forward gain for stability of the system. Haddad *et al*. (2007) investigated sufficient conditions for finite-time stability using continuous Lyapunov function to develop a general framework for finite-time stability analysis based on vector Lyapunov function. It is possible to reset the state variables of impulsive dynamic systems to an equilibrium state using both scalar and vector Lyapunov functions. Haddad and Nersesov (2007) also extended the Lyapunov theory for continuous-time systems to address stability and control design of impulsive dynamic systems via vector Lyapunov functions for a large scale impulsive dynamic system. It is shown in the study that partial stability for state dependent impulsive dynamical systems can be address via vector Lyapunov functions. Haddad and Nersesov (2008) further developed a finite-time stabilizing controller for impulsive dynamic systems that are robust against full modeling uncertainty.

Li and Soh (1999) derive necessary conditions for the stability of dynamic systems in the sense of Lyapunov which are used to study the stability of discontinuous dynamic systems, including fuzzy systems and impulsive differential systems. Litsyn *et al*. (2000) discussed the parameters of stabilization control procedure for linear controlled planar systems which admit stabilization via the linear hybrid feedback controls. A matrix decomposition method had also been used to study the stability of the equilibrium state of non-autonomous linear systems as in Abdel-Rahman and Ahmadi (1986). This technique

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systematically provides sufficient stability and asymptotic stability conditions for such systems, several criteria regarding the stability of linear systems with time-varying coefficients were developed.

The literature search indicates that generally the authors of the previous investigation on the stability of dynamic systems have directed their studies to special functions such as the Lyapunov function for describing the various stability situations of the dynamic systems. It is however more convenient for simplified dynamic systems to determine the systems stability response by using the fundamental solutions as described in this study. The basic agreement is to feedback controlled parameters of the system.

Negative feedback generally caused variables to return towards their original value and therefore act as stabilizing forces in dynamic systems. However to guaranty stability, the negative feedback must act gently to prevent the oscillation of variables about their equilibrium. This can be achieved by the careful selection of the feedback parameter. A feedback structure is proposed for the beat-up mechanism to regulate the instability experienced by the mechanism during operation.

In this research, we extended the general knowledge of transient response analysis to predict the response of the narrow loom beat-up mechanism when a feedback element such as a viscous damper is introduced to control the stability of the system.

MATERIALS AND METHODS

Fundamental factors that govern the qualitative behavior of dynamic systems needed be established. The intent is to focus the analysis on the derivation of basic proposition about the factors that determine the stability of the system in the elementary context of one dimensional autonomous system. Damping is an effective means for attenuating vibration response but must be placed in the vibration energy transmission path to effectively attenuate the response of the system. The beat-up mechanism of the narrow loom as shown in Fig. 1 is modeled as a torsional system comprising a shaft of torsional stiffness K, a beam of mass-moment of inertia J_b which represents inertia body for the beater and slay bar rotating about the axis of rotation of the shaft. Torque T_θ is delivered on the beater. The system is damped with a viscous damper of coefficient, B and modeled as a Single Degree of Freedom (SDOF) torsional system as shown in Fig. 2. The damping element is located to dissipate the energy generated as a result of the impact experienced during the operation of the mechanism. It is deliberately introduced as a feedback element for purpose of returning the system to its equilibrium state after

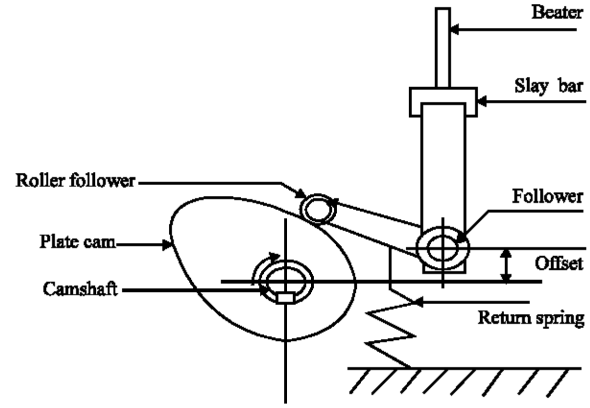

Fig. 1: Schematic diagram of the model mechanism (Raji, 2000)

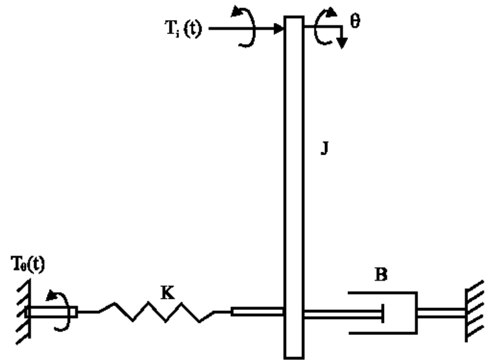

Fig. 2: Beater System SDOF model

experiencing the impulsive torque. The corresponding differential equations describing the model are obtained as expressed in Eq. 1:

$$J\theta + B\theta + K\theta = T_\theta(t) + T_i(t) \quad (1)$$

$T\theta$ is the torque associated with the turning effect of the follower on the beater and T_i is the impulsive torque on the beater as it beats the weft into the yarn.

The resulting equation identifies with a linear second-order dynamic system. The damping ratio ζ and undamped natural frequency ω_n of the system are expressed respectively as:

$$\zeta = \frac{B}{2\sqrt{JK}} \text{ and } \omega_n = \sqrt{\frac{K}{J}} \quad (2)$$

The system model can thus be expressed as:

$$\ddot{\theta} + 2\zeta\omega_n\dot{\theta} + \omega_n^2\theta = T_\theta + T_i \quad (3)$$

The turning effect which is a continuous torque is considered constant as continuously delivered on the beater shaft.

While the impulsive torque resulting from the beat-up action is a momentary turning effect. Both T_θ and T_i applied will contribute to the determination of the response.

The responses due to the two forcing functions could be analyzed separately and use the principle of superposition to determine the overall response of the system, $\theta(t) = \theta_\theta(t) + \theta_i(t)$.

It is important to note that the continuous torque is considered for step response while the impulsive torque is considered for impulse response.

To complete the formulation of the problem the initial conditions of the system is specified as in Eq. 4:

$$\theta(0^-) = \theta_0 \text{ and } \dot{\theta}(0^-) = \dot{\theta}_0 \tag{4}$$

Equation 3 and the appropriate initial conditions (4) constitute the appropriate model equations, the solution of which can now be conveniently obtained by Laplace transform.

Let the Laplace transform quantity of θ be denoted by θ, we then can obtain:

$$\theta(s) = \left[\frac{1}{S^2 + 2\zeta\omega_n + \omega^2{}_n}\right]T(s) + \frac{(s + 2\zeta\omega_n)\theta_0 + \dot{\theta}_0}{s^2 + 2\zeta\omega_n s + \omega^2{}_n} \tag{5}$$

Hence for a unit-step input of the turning torque $T(s) = T_\theta$, θ is obtained as:

$$\theta_\theta(t) = \frac{1}{\omega^2{}_n}\left\{1 + \frac{1}{2\sqrt{\zeta^2-1}}\left[\frac{1}{-\zeta+\sqrt{\zeta^2-1}}e^{-\omega_n\left(\zeta-\sqrt{\zeta^2-1}\right)\tau} + \frac{1}{\zeta+\sqrt{\zeta^2-1}}e^{-\omega_n\left(\zeta+\sqrt{\zeta2-1}\right)\tau}\right]\right\}$$
$$+\left[\frac{\omega_n\left(\zeta+\sqrt{\zeta^2-1}\right)\theta_0+\theta_0}{2\omega_n\sqrt{\zeta^2-1}}\right]e^{-\omega_n\left(\zeta+\sqrt{\zeta^2-1}\right)\tau} - \left[\frac{\omega_n\left(\zeta-\sqrt{\zeta^2-1}\right)\theta_0+\dot{\theta}_0}{2\omega_n\sqrt{\zeta^2-1}}\right]e^{-\omega_n\left(\zeta+\sqrt{\zeta^2-1}\right)\tau} \tag{6}$$

And for the unit-impulse torque $T(s) = T_i$, θ is obtained as:

$$\theta_i(t) = \frac{1}{2\omega_n\sqrt{\zeta^2-1}}e^{-\omega_n\left(\zeta-\sqrt{\zeta^2-1}\right)t}\frac{1}{2\omega_n\sqrt{\zeta^2-1}}e^{-\omega_n\left(\zeta+\sqrt{\zeta^2-1}\right)t}$$
$$+\left[\frac{\omega_n\left(\zeta+\sqrt{\zeta^2-1}\right)\theta_0+\dot{\theta}_0}{2\omega_n\sqrt{\zeta^2-1}}\right]e^{-\omega_n\left(\zeta-\sqrt{\zeta^2-1}\right)t} - \left[\frac{\omega_n\left(\zeta-\sqrt{\zeta^2-1}\right)\theta_0+\dot{\theta}_0}{2\omega_n\sqrt{\zeta^2-1}}\right]e^{-\omega_n\left(\zeta+\sqrt{\zeta^2-1}\right)t} \tag{7}$$

RESULTS AND DISCUSSION

The responses for the unit step torque and the unit impulse torque are programmed in the Microsoft Excel environment. For the purpose of illustration of the results, the following parameter values were employed:

$$\omega_n = 1, \theta_0 = 0, \dot{\theta}_0 = 1$$

The values for the responses are tabulated in Table 1 and 2. The overall response due to the two forcing functions is determined by principle of superposition and tabulated in Table 3. Graphical interpretations of the responses are presented in Fig. 3-5.

Figure 3 and 4 shows the separate decay effect of the damping element on the beater system. It is observed that the turning torque on the system by the shaft introduces a high level of instability on the system. The system is damped by the dashpot element representing the desire to achieve stability targeting steady state response of the beater system. The influence of the damping element on the performance characteristics is strongly dependent upon the damping coefficient of the damper employed. Thus, the response characteristics of the beater system are established for five damping coefficients as shown in Fig. 5. The peak response of the system increases

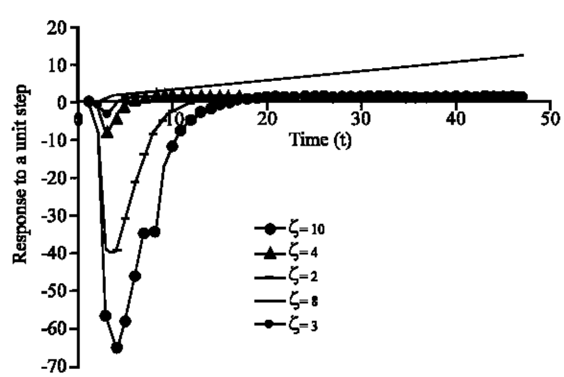

Fig. 3: Response of beater system to a unit step: $\theta_0 = 0$, e↓0≠ 0

Table 1: System response table for unit step input of applied torque Tθ

	System response to a unit step input				
Time (t)	ζ = 10	ζ = 8	ζ = 4	ζ = 3	ζ = 2
0	-7.89945	-0.60993	-2.4641	-1.52982	-0.54919474
10	-55.8082	-38.5473	-8.65859	-3.27154	0.458842883
20	-64.5513	-39.2002	-4.12228	-0.36197	1.408403047
30	-57.5719	-30.6546	-1.10235	0.723868	1.71428895
40	-45.9076	-21.3427	0.234111	1.033942	1.957662524
50	-34.337	-13.8349	0.747452	1.129035	2.197200663
60	-34.5991	-8.47217	0.932035	1.172805	2.436624205
70	-17.0472	-4.88586	0.997107	1.205231	2.67605813
80	-11.4711	-2.58496	1.021043	1.235266	2.91549457
90	-7.48667	-1.15029	1.031319	1.264814	3.154931345
100	-4.70558	-0.27421	1.03717	1.294265	3.394368157
110	-2.7983	0.252327	1.041616	1.323696	3.633804972
120	-1.50808	0.564846	1.045621	1.353124	3.873241788
130	-0.64483	0.748467	1.040949	1.382551	4.112678604
140	-0.07242	0.855455	1.053318	1.411978	4.352115419
150	0.304306	0.917358	1.057132	1.441405	4.591552235
160	0.550671	0.952962	1.060943	1.470832	4.830989051
170	0.790909	0.973334	1.064752	1.500259	5.070425866
180	0.81464	0.98494	1.068561	1.529686	5.309862682
190	0.881513	0.991525	1.07237	1.559113	5.549299498
200	0.924467	0.995249	1.076179	1.58854	5.788736314
210	0.951969	0.997349	1.079988	1.617967	6.028173129
220	0.969526	0.99853	1.083797	1.647394	6.267609945
230	0.980705	0.999192	1.087606	1.676821	6.507046761
240	0.987806	0.999563	1.091415	1.706248	6.746483576
250	0.992307	0.999771	1.095224	1.735675	6.985920392
260	0.995154	0.999887	1.099033	1.765102	7.225357208
270	0.996952	0.999953	1.102842	1.794529	7.464794023
280	0.998086	0.999989	1.106651	1.823957	7.704230839
290	0.9988	1.00001	1.11046	1.853384	7.943667655
300	0.999248	1.000022	1.114269	2	8.18310447
310	0.99953	1.00002	1.118078	1.912238	8.422541286
320	0.999706	1.000034	1.121887	1.941665	8.661978102
330	0.999817	1.000037	1.125696	1.971092	8.901414917
340	0.999886	1.000039	1.129505	2.000519	9.140851733
350	0.999929	1.000041	1.133314	2.029946	9.380288549
360	0.999956	1.000043	1.137123	2.059373	9.619725364
370	0.999973	1.000044	1.140932	2.0888	9.85916218
380	0.999984	1.000045	1.144741	2.118337	10.098599
390	0.99999	1.000047	1.14855	2.147654	10.33803581
400	0.999994	1.000048	1.152359	2.177081	10.57747263
410	0.999997	1.000049	1.156167	2.206508	10.81690944
420	0.999998	1.00005	1.159976	2.235935	11.05634626
430	0.999999	1.000052	1.163785	2.265362	11.29578307
440	1	1.000053	1.167594	2.294769	11.53521989
450	1	1.000054	1.171403	2.324216	11.77465671

Table 2: System response table for unit Impulse input of applied torque T

	System response to a unit impulse input				
Time (t)	ζ = 10	ζ = 8	ζ = 4	ζ = 3	ζ = 2
0	0	0	0	0	0
10	0.060882	0.067271	0.072498	0.06358	0.039605
20	0.03688	0.035919	0.020356	0.011434	0.002717
30	0.022341	0.019179	0.005716	0.002056	0.000186
40	0.013534	0.01024	0.001605	0.00037	1.28E-05
50	0.008198	0.005468	0.000451	6.65E-05	8.77E-07
60	0.004966	0.00292	0.000127	1.20E-05	6.02E-08
70	0.003008	0.001559	3.55E-05	2.15E-06	4.13E-09
80	0.001822	0.000832	9.98E-06	3.87E-07	2.83E-10
90	0.001104	0.000444	2.80E-06	6.95E-08	1.94E-11
100	0.000669	0.000237	7.86E-07	1.25E-08	1.33E-12
110	0.000405	0.000127	2.21E-07	2.25E-09	9.14E-14
120	0.000245	6.77E-05	6.20E-08	4.04E-10	6.27E-15
130	0.000149	3.61E-05	1.74E-08	7.27E-11	4.3E-16
140	9.00E-05	1.93E-05	4.89E-09	1.31E-11	2.95E-17
150	5.45E-05	1.03E-05	1.37E-09	2.35E-12	2.02E-18
160	3.30E-05	5.50E-06	3.85E-10	4.23E-13	1.39E-19
170	2.00E-05	2.94E-06	1.08E-10	7.61E-14	9.52E-21
180	1.21E-05	1.57E-06	3.04E-11	1.37E-14	6.53E-22
190	7.35E-06	8.37E-07	8.53E-12	2.46E-15	4.48E-23
200	4.45E-06	4.47E-07	2.40E-12	4.42E-16	3.07E-24
210	2.70E-06	2.39E-07	6.73E-13	7.96E-17	2.11E-25
220	1.63E-06	1.27E-07	1.89E-13	1.43E-17	1.45E-26
230	9.89E-07	6.80E-08	5.30E-14	2.57E-18	9.92E-28
240	5.99E-07	3.63E-08	1.49E-14	4.63E-19	6.81E-29
250	3.63E-07	1.94E-08	4.18E-15	8.32E-20	4.67E-30
260	2.20E-07	1.04E-08	1.17E-15	1.50E-20	3.2E-31
270	1.33E-07	5.53E-09	3.30E-16	2.69E-21	2.2E-32
280	8.07E-08	2.95E-09	9.26E-17	4.84E-22	1.51E-33
290	4.89E-08	1.58E-09	2.60E-17	8.70E-23	1.03E-34
300	2.96E-08	8.42E-10	7.30E-18	1.56E-23	7.09E-36
310	1.79E-08	4.50E-10	2.05E-18	2.81E-24	4.87E-37
320	1.09E-08	2.40E-10	5.75E-19	5.06E-25	3.34E-38
330	6.58E-09	1.28E-10	1.62E-19	9.10E-36	2.29E-39
340	3.99E-09	6.84E-11	4.54E-20	1.64E-26	1.57E-40
350	2.42E-09	3.65E-11	1.27E-20	2.94E-27	1.08E-41
360	1.46E-09	1.95E-11	3.58E-21	5.29E-28	7.39E-43
370	8.86E-10	1.04E-11	1.00E-21	9.52E-29	5.07E-44
380	5.37E-10	5.56E-12	2.82E-22	1.71E-29	3.48E-45
390	3.25E-10	2.97E-12	7.92E-23	3.08E-30	2.39E-46
400	1.97E-10	1.59E-12	2.22E-23	5.54E-31	1.64E-47
410	1.19E-10	8.47E-13	6.24E-24	9.96E-32	1.12E-48
420	7.23E-11	4.52E-13	1.75E-24	1.79E-32	7.7E-50
430	4.38E-11	2.41E-13	4.92E-25	3.22E-33	5.28E-51
440	2.65E-11	1.29E-13	1.38E-25	5.79E-34	3.62E-52
450	1.61E-11	6.88E-14	3.88E-26	1.04E-34	2.49E-53

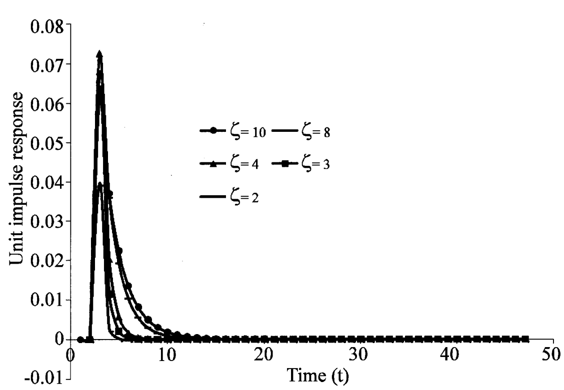

Fig. 4: Response of beater system to unit impulse: θ_0=0, C↓0≠0

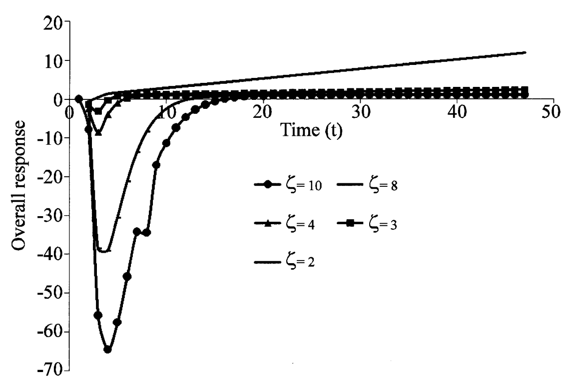

Fig. 5: Overall transient response of beater system; θ_0=0, C↓0≠0

Table 3: Overall system response table for the beater system

	Overall system response				
Time (t)	$\zeta = \tilde{10}$	$\zeta = 8$	$\zeta = 4$	$\zeta = 3$	$\zeta = 2$
0	-7.89945	-0.60993	-2.4641	-1.52982	-0.54919474
10	-55.747318	-38.480029	-8.586092	-3.20796	0.498447956
20	-64.51442	-39.164281	-4.101924	-0.350536	1.411119875
30	-57.549559	-30.635421	-1.096634	0.725924	1.714475319
40	-45.894066	-21.33246	0.235716	1.034312	1.957675308
50	-34.328802	-13.829432	0.747903	1.1291015	2.19720154
60	-34.594134	-8.46925	0.932162	1.172817	2.436624265
70	-17.044192	-4.884301	0.9971425	1.20523315	2.676058134
80	-11.469278	-2.584128	1.021053	1.23526639	2.915494571
90	-7.485566	-1.149846	1.0313218	1.26481407	3.154931346
100	-4.704911	-0.273973	1.0371708	1.29426501	3.394368157
110	-2.797895	0.252454	1.0416162	1.323696	3.633804972
120	-1.507835	0.5649137	1.0456211	1.353124	3.873241788
130	-0.644681	0.7485031	1.040949	1.382551	4.112678604
140	-0.07233	0.8554743	1.053318	1.411978	4.352115419
150	0.3043605	0.9173683	1.057132	1.441405	4.591552235
160	0.550704	0.9529675	1.060943	1.470832	4.830989051
170	0.790929	0.97333694	1.064752	1.500259	5.070425866
180	0.8146521	0.98494157	1.068561	1.529686	5.309862682
190	0.88152035	0.99152584	1.07237	1.559113	5.549299498
200	0.92447145	0.99524945	1.076179	1.58854	5.788736314
210	0.9519717	0.99734924	1.079988	1.617967	6.028173129
220	0.96952763	0.99853013	1.083797	1.647394	6.267609945
230	0.98070599	0.99919207	1.087606	1.676821	6.507046761
240	0.9878066	0.99956304	1.091415	1.706248	6.746483576
250	0.99230736	0.99977102	1.095224	1.735675	6.985920392
260	0.99515422	0.99988701	1.099033	1.765102	7.225357208
270	0.99695213	0.99995301	1.102842	1.794529	7.464794023
280	0.99808608	0.999989	1.106651	1.823957	7.704230839
290	0.99880005	1.00001	1.11046	1.853384	7.943667655
300	0.99924803	1.000022	1.114269	1.882811	8.18310447
310	0.99953002	1.00002	1.118078	1.912238	8.422541286
320	0.99970601	1.000034	1.121887	1.941665	8.661978102
330	0.99981701	1.000037	1.125696	1.971092	8.901414917
340	0.999886	1.000039	1.129505	2.000519	9.140851733
350	0.999929	1.000041	1.133314	2.029946	9.380288549
360	0.999956	1.000043	1.137123	2.059373	9.619725364
370	0.999973	1.000044	1.140932	2.0888	9.85916218
380	0.999984	1.000045	1.144741	2.118337	10.098599
390	0.99999	1.000047	1.14855	2.147654	10.33803581
400	0.999994	1.000048	1.152359	2.177081	10.57747263
410	0.999997	1.000049	1.156167	2.206508	10.81690944
420	0.999998	1.00005	1.159976	2.235935	11.05634626
430	0.999999	1.000052	1.163785	2.265362	11.29578307
440	1	1.000053	1.167594	2.294769	11.53521989
450	1	1.000054	1.171403	2.324216	11.77465671

tremendously as the damping coefficient is increased, except for damping coefficients range $3<\zeta<4$ for which the system quickly attained steady state. This places a limiting boundary beyond which the system will experience very high resonant at start of operation and as shown in Fig. 3 and 4, a damping coefficient below the lower boundary subjects the system to uncontrolled response. Figure 3 depict the understanding that it is the applied turning torque that is mostly responsible for the early instability of the system.

CONCLUSION

The transient response of a narrow loom beater mechanism with a damping element is investigated to demonstrate the significance dynamic of the damping element introduced into the beater system. The beater system is modeled as a linear second-order dynamic system.

Simulation results are obtained for the transient response of the system for five damping coefficients. A comparison of the responses reveals that the system stability could be controlled by the introduction of the damping element.

The system is acceptably damped within certain range of damping ratio beyond which resulting response peak causes early experienced instability that may lead to the failure of the system.

The discontinuities in the response of the system gradually decay in amplitude until the imbalance disappears. The damping coefficient of the damping element determines the rate of decay and the steady state of the system. Understanding the leverage points of the system can allow a better control of the mechanism.

In the damped system the negative feedback is constantly correcting the system instability by driving the system to its desired state. The speed at which the system comes to equilibrium depends on the system's degree of damping. In conclusion, understanding the degree of damping in the system is useful for controlling the system stability.

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