An Experimental Driven Approach of Braille Embosser Print Head Design Using Analytical and Computational Techniques

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***Abstract*— This paper presents an experiment driven approach for the design of a braille embosser print head characterised by impact generated by electromagnetic force. The developmental work presented here is an experimental driven approach for design of a braille embosser which is essentially an impact printer, that convert text as braille output. The problem with bad quality printing of the braille dots including waviness and vibration, which limit the operating speed of the printer, is specially addressed. In this research study variation in printing quality are caused by non linear dynamics coupled with other factors such as proper material, vibration, specific electro-mechanical design issue and many more. This approach clearly shows that even a successful product design at laboratory level requires continuous experimentation to achieve the desired goal. The experiments results show that some mechanical parameters are critical in order to get satisfactory quality on the braille text print. Altogether, this approach contributes to better knowledge and understanding about various aspects that needs to be considered while designing similar types of products.**

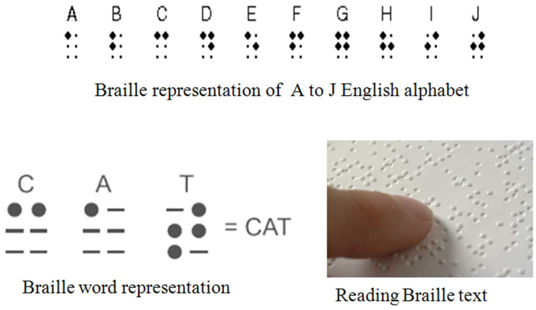
Keywords— Braille impact dynamics, braille print head modeling, impact printer, contact mechanics, solenoid.

1 Introduction

Braille is the language used by the vision impaired person for their study and written communication. Such braille text is printed through indentation of dots appearing in specified patterns on a special quality paper (120-140 gsm) as shown in Fig.1. This dots are produced by impact solenoid which has a spring-loaded ferromagnetic core placed inside a coil. When a dot is needed, a current pulse is sent through the coil. This creates an electromagnetic force on the core in the direction perpendicular to the paper, forcing it to impact the paper and create necessary indentation .This research has its focus on the development of a low cost braille embosser which can provide quality braille output for the students & communities affected by the problem of blindness. In order to obtain quality braille output it is important to get a certain amount of impact energy. If the electrical energy supplied to the solenoid is too low, the dots will be weak and difficult to read. On the contrary if it is too large, there will be risk for through holes in the paper as well as smudging the learner. This is the process of creating braille printout done by braille printer.

Wassmuth, E-1991[1] first studied the importance of an active control for an impact matrix print head. The controller proposed for this uses digital simulation techniques. Marielle Piron & P. Sangha [2] describes a general method for preliminary design of fast-acting solenoid actuators. An analog feedback controller has been proposed and tested which is claim to enhances the performance of a moving-coil actuator [3]. Jenny Jerrelind [4] analyze a combined control scheme relying on feedback-based local control in the vicinity of periodic system responses and global control based on a coarse-grained approximation to the nonlinear dynamics associated to a braille printer using impact solenoid. The steady state braille impact solenoid dynamics has been described by changing the position of back stop. Harry Dankowicz and Petri T. Piiroinen [5] [6] has proposed a necessary mathematical technique for modeling the presence of discontinuities in dynamical systems. All of these though can provide some insight into this process like optimizing the performance of solenoid, yet fails to encapsulate the primary issue such as how to control vibration of such an impact device while it is operating at very high speed as well as in case of interpoint printing , how to constrain & control the quality of the dots produced which can not confuse the reader. This has resulted present research team to adopt an experiment driven design approach. To further investigate the problem with printing quality of braille printer caused by the non-linear dynamics in the system, resulted a number of prototype system designed, manufactured tested both for performance and output quality. Developed braille embosser is shown in Fig.2. This braille printer developed by CMERI has the capacity to produce double-sided Braille text, which is managed by a mixture of convex and concave shapes of the tip part of core and corresponding anvil. In this type of embosser eleven solenoid are fixed in a printing head, as shown in Fig.2b. This print head consist solenoid, anvil and solenoid supporting frames, rubber and paper supports. When a dot is needed, a current pulse is sent through the coil of solenoid. This creates an electromagnetic force on the core in the direction perpendicular to the paper, forcing it to impact the paper and the front stop.

The core is subsequently pulled back by the helical spring. The return is damped by a back stop in order to force the core to rest before the next excitation pulse. A schematic diagram explaining the operating principle of the components of system is shown in Fig. 3.



Braille representation of A to J English alphabet

Braille word representation

Reading Braille text

Fig. 1. Braille text in specific pattern

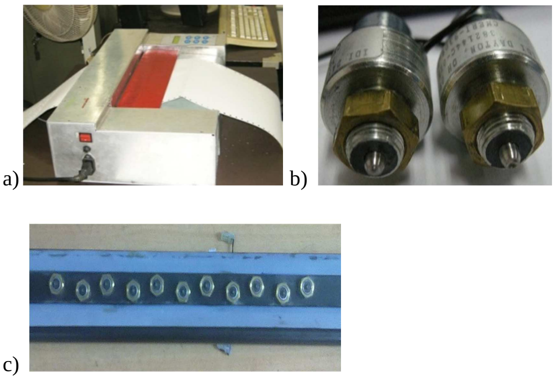


Fig. 2. a) Braille Embosser developed
b) CMERI-9309 Solenoids used in print head
c) Print head

The process of numerical simulation along with product visualization and three dimensional interference check has been considered an essential part to design of such a complex electro-mechanical system. This paper therefore presents a experimental data derived methodology i.e. experimental driven approach to design & developing Braille embosser text prints technology. This approach is further depicted in Fig.4, which clearly shows that for a successful product design cycle even at laboratory level requires continuous experimentation to achieve satisfactory design of the system.

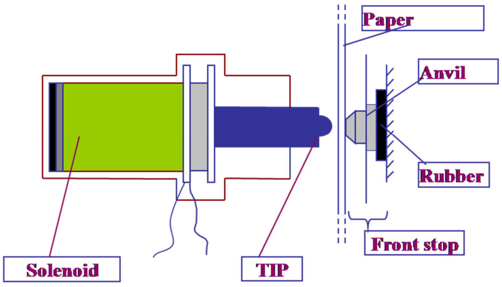


Fig. 3. Schematic diagram of system

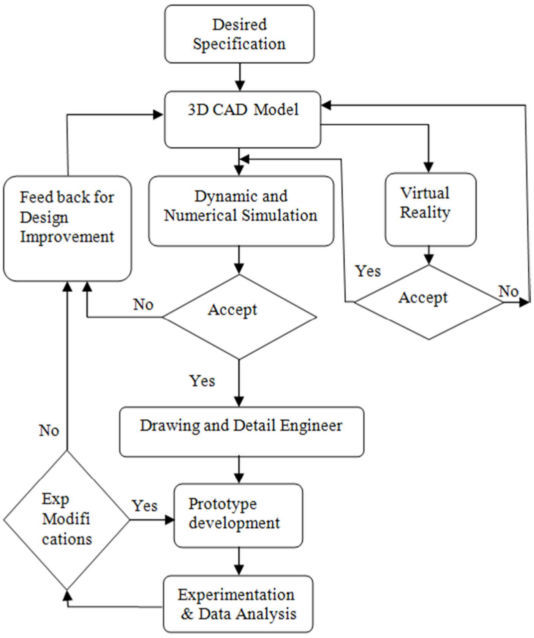


Fig. 4. Flow chart of experimental driven approach

2 Details of Modelling

The print head of the present model consist of a stepper motor with a rack and pinion arrangement for movement of print head in longitudinal direction with respect to a guide rod as shown in Fig.5

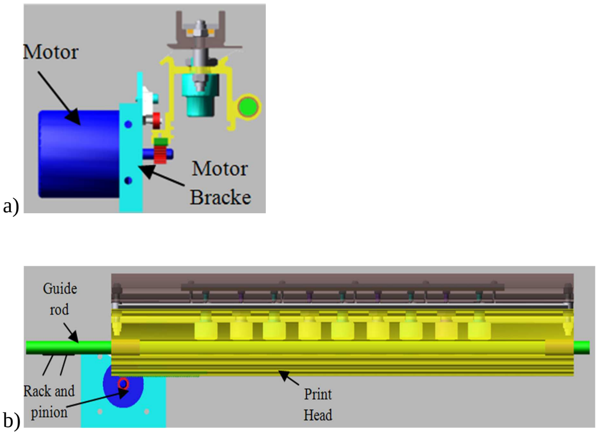


Fig. 5. a) Side view and b) front view of CAD model of print head arrangement

The printing process is caused by the impact created by solenoid mounted at print head as shown in Fig 6b. The motion of the individual parts of the impact solenoid as well as the contact events can be considered as rigid-body mathematical modeling. It is there for reasonable to assume that the solenoid is a three-degree-of-freedom system consisting of a mass representing the front stop, a mass representing the back stop and the core, each of which move independently [4-6]. In the current design, the front and back stops are highly damped.

This supports the simplifying assumption that these masses are at rest prior to being hit by the core. besides, contact between the core and the front and back stops will be modeled as a purely inelastic collision implying that their relative velocity after impact is zero. With these assumptions, it is possible to simplify the system to a one-degree-of-freedom system that contains only the movement of the core, as shown in Fig.6. The motion of the impact solenoid is now modeled using a single-degree-of-freedom system. Here spring-loaded core is excited by an electromagnetic force generated by a current pulse through a surrounding coil.

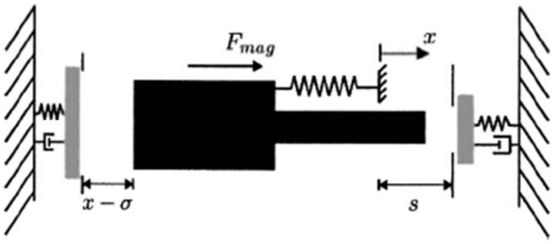


Fig. 6. One degree of freedom model of print head [4]

Specifically, let the horizontal displacement of the core be denoted by x, such that x ≤ σ (σ denotes position of back stop) corresponds to contact with the back piece and x ≥s (s denotes position of front Anvil) corresponds to contact with the front anvil. It is assumed that the restoring spring is pre-compressed, in such a way that, in the absence of friction and electromagnetic forces, equilibrium would be attained for x < 0. The main part of deformation is assumed to occur in rubber material, i.e. it has been assumed that the stiffness and the damping are used to model the characteristics of the rubber and its mountings.

In the absence of contact between the printer head and the two stops, the dynamics of the printer head are governed by the differential Equation given by [6],

$$m_{core}\,\ddot{x} + k(x+d) + \mu g m_{core} sign(u) = \frac{dL}{dx}(x) I^2(t) \tag{1}$$

Different nomenclatures are

m_{core} = Mass of core, kg

m_{anvil} =Mass of anvil, kg

k =Stiffness of spring, N/m

d =Preload of spring, m

µ =Coefficient of kinetic friction

L(x) =Coil inductance, N/A^2 m

I(t) =Externally imposed coil current, A

K_{anvil} = Stiffness of Anvil material, N/m

C_{anvil} = Damping of Anvil, N.s/m

d_{anvil} = Preload of Anvil, m

g = Gravitational Acceleration, m/s^2

let the state of the dynamical system governing the impact solenoid be given by

$$\mathrm{X} = (x, \dot{x}, t)^{\mathrm{T}} \tag{2}$$

Where ẋ corresponds to u , the equations of motion for the free flight phase thus take the form

$$\dot{X} = (\dot{x}, \ddot{x}, 1)^{\mathrm{T}} \tag{3}$$

or

$$\dot{X} = \left[u, \quad \frac{1}{m_{\text{core}}}\left\{-k(x+d) - \mu g m_{\text{core}}\,\mathrm{sign(u)} + \frac{dL}{dx}(x)\,\mathrm{I}^2(t)\right\}, \quad 1\right]^T \tag{4}$$

Please refer equation (1).

These equations[6], govern the motion provided that

$$h_{front}\,(x) = x - s \le 0 \tag{5}$$

$$h_{back}\,(x) = x - \sigma \le 0 \tag{6}$$

where $h_{front}(x)$ & $h_{back}(x)$ two event functions only.

At the moment that contact is established between the core and the anvil, h_{front} becomes zero. Assuming that the collision between the core and the anvil is modeled as inelastic [4], the function that maps the final state during the flight phase to the initial state of the front contact phase becomes

$$g_{front\ Impact}\,(x) = \left(x, \frac{m_{\text{core}}}{m_{\text{core}} + m_{\text{anvil}}}\,\dot{x}, t\right)^{\mathrm{T}} \tag{7}$$

During the front-contact phase, the vector field is given by

$$f_{front\ impact}(x) = \left[u, \quad \frac{1}{m_{\text{core}} + m_{\text{anvil}}}\left\{-k(x+d) - \mu g\, m_{\text{core}}\,\mathrm{sign(u)} + \frac{dL}{dx}(x)\mathrm{I}^2\,(t) - k_{\text{anvil}}(\mathrm{x} - \mathrm{s} + d_{\text{anvil}}) - C_{\text{anvil}}\mathrm{u}\right\}, \quad 1\right]^T \tag{8}$$

This vector field applies as long as [6],

$$h_{front\ release}\,(x) = x - s \ge 0 \tag{9}$$

At the moment that contact is established between the core and the back piece, h_{back} becomes zero. As the back piece is modelled as a mass-less (non-linear) spring and damper, there is no change in the state at this impact, i.e.

$$g_{back\ Impact}\,(x) = x \tag{10}$$

During the back-contact phase, the vector field is given by

$$\mathrm{f}_{\text{back impact}}(\mathrm{x}) = \left[u, \quad \frac{1}{m_{\text{core}} + m_{\text{anvil}}}\left\{-k(x+d) - \mu g\, m_{core}\,\mathrm{sign(u)} + \frac{dL}{dx}(x)\mathrm{I}^2\,(t) - k_{\text{back,1}}(\mathrm{x} - \sigma) - k_{\text{back,2}}(\mathrm{x} - \sigma)^2 - C_{\text{back}}\,\mathrm{u}\right\}, \quad 1\right]^T \tag{11}$$

Thus force during contact depends upon the inelastic impact between moving mass and anvil or back stop. The main part of deformation is assumed to occur in rubber material, i.e. it has been assumed that the stiffness and the damping are used to model the characteristics of the rubber and its mountings.

From Equation 8 of front impact, impact force during contact phase can be obtained. The various mechanical parameters [4] are as per Table 1,

TABLE 1

Parameter Used in various equations	
Mechanical Parameters	***value***
m_{core}	4.32×10^{-3} kg
m_{anvil}	1.22×10^{-3}kg
k	100 N/m
d	0.002 m
k_{anvil}	335×10^{3} N/m
$k_{back,1}$	5×10^{8} N/m
k_{bck2}	4×10^{4} N/m
C_{anvil}	37 N/s
C_{back}	60 N/s
d_{anvil}	0.0002 m
s	0.00380 m
σ	0 m
L_0	0.1678 N/A^2
L_1	30.845 N/A^2 m

The dots on the paper should have 0.5 mm height and diameter 1.5 mm. for good quality. To produce such indentation the solenoid core must deliver impact energy of 8 to 10 mJ for quality printing on 120-140 gsm paper [7]. This implies, for the design studied, that the impact velocity should be in between 1.5 to 2.5 m/s.

Here

$$F_{mag} = (L_1 x + L_0)\, I^2\,(t) \cong \frac{dL}{dx}(x) \mathrm{I}^2\,(t) \qquad (12)$$

$at\ t = 2.5\ ms\ , x = 0.00380$

and for $t = 2.5\ ms$, $I = 5\ Amp$.

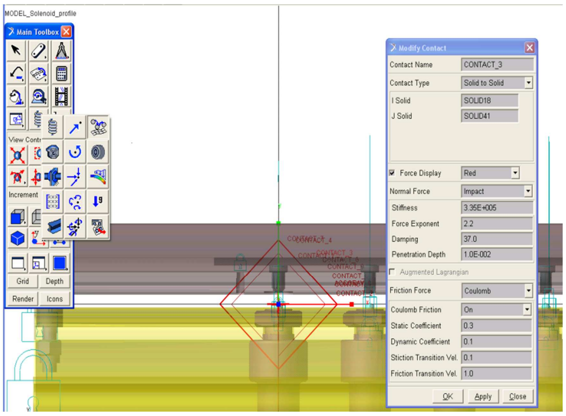
Thus from equation no. 8 $f_{front\ impact}$ can be calculated

$$f_{front\ impact}(x) = \left[1.528,\ \frac{1}{0.00554}\ (-72.95)\ , 1\right]^T \qquad (13)$$

Thus on onset of contact between front anvil and solenoid plunger tip, the value of contact force is nearly 73 N. This Contact force is responsible for the indentation of dots on the paper, as paper is embossed between the solenoid plunger tip having dimple profile and front anvil having cavity. The main objective of this numerical work is to find-out parameters to guide a most suitable design for the system, which can provide a quality braille output. To verify the above, ADAMS$^{@}$ model is developed.

2.1 Simulation of Contact Force

The 3-D CAD model of the print head, as shown in Fig.5, is transferred into an ADAMS$^{@}$ multi-body model using the parasolid interface embedded in INVENTOR$^{@}$. The parasolid CAD file format is considered as a reliable file format for the files to be import in the ADAMS$^{@}$ as there is negligible geometry loss. Perfect geometry is required for the 3D contact problem. Some parts are kept hidden for good visual effect of the simulation. The multi-body model of the print head is shown in Fig.7. The bearings to support the guide shafts are described by revolute and cylindrical joints. A fixed joint is added to every solenoid body and revolute joint to corresponding shaft, so that the force applied to the moving core is transferred onto the anvil.



Contact Name: CONTACT_3
Contact Type: Solid to Solid
I Solid: SOLID18
J Solid: SOLID41
☑ Force Display: Red
Normal Force: Impact
Stiffness: 3.35E+005
Force Exponent: 2.2
Damping: 37.0
Penetration Depth: 1.0E-002
☐ Augmented Lagrangian
Friction Force: Coulomb
Coulomb Friction: On
Static Coefficient: 0.3
Dynamic Coefficient: 0.1
Stiction Transition Vel.: 0.1
Friction Transition Vel.: 1.0

Fig. 7. Multi body model of print head

By defining step function we know that the damping force is defined as a cubic function of penetration depth [8]. To avoid the function discontinuity caused by the dramatic variation of the damping force while contact-collision occurs, the damping force is set to zero when the penetration depth of the two contacted bodies is zero, and approaches a maximum value of force, when the specified penetration depth is reached. Two types of contact are modeled between the surfaces of the contacted bodies. One type is discontinuous contact, using an approach similar to free falling bouncing ball approach. The other is continuous contact, where the contact is defined as a nonlinear spring. Two algorithms for the computation of contact force are available in ADAMS$^{@}$, the restitution method and the impact method.

Considering the computing efficiency and accuracy, the latter one is adopted in this paper. Necessary parameters for this method are shown in Table 1. The contact force computed by this method is composed of two parts, the elastic force caused by the deforming components and the damping force caused by the relative deforming velocity.

2.2 Simulation Results

Thus it's very clear from analysis that the contact between solenoid tip and anvil is a inelastic impact and value of contact force is depends upon the translation velocity. The values of contact force calculated from ADAMS$^{@}$ are 85 N & 65 N shown in Fig.8, which varies from the analytical one obtained by Equation 13. This may be due to the dimple profile on solenoid tip (Convex and Concave surface) considered in case of ADAMS$^{@}$. A major deviation from the flat tip assumption used in equation 13. It is also noticeable that in ADAMS$^{@}$ analysis coefficient of restitution is not considered which is related with velocity changes.

In the case of the Braille printer, the actual impact velocity (shown in Fig. 9) with the front stop is of importance as this control the quality of the dot produced. Moreover, it is also important to ensure that at most a single impact occur between the solenoid and the front stop during each cycle of the excitation.

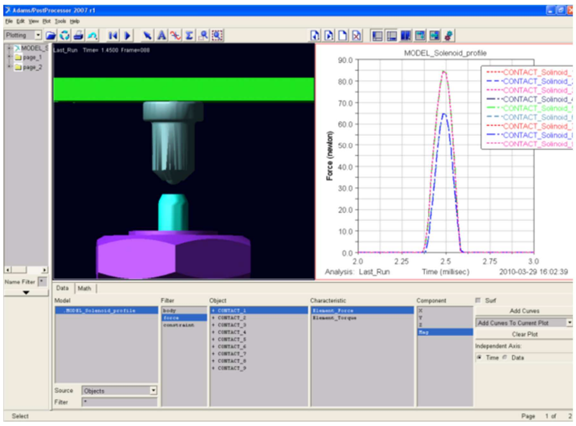


Fig. 8. Contact force representation

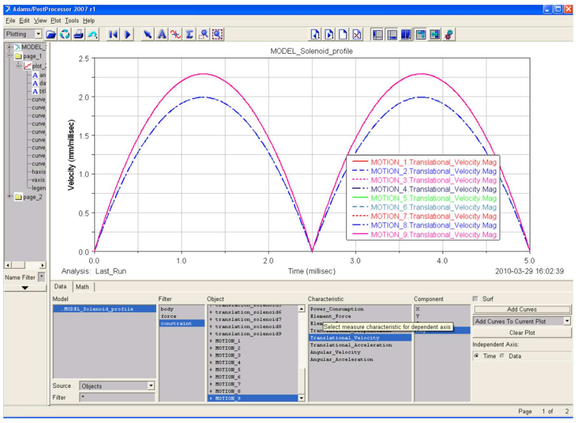


Fig. 9. Velocity representation for analysis -1

3 *Experimental Setup to Verify Analytical and Computational Results*

An experimental setup is constructed as per schematic plan shown in Fig.10 to facilitate measurement of the impact force , produced by the contact between solenoid tip and anvil in the braille printing system .A low level force sensor "Kastler type-9205" was used for this purpose. A printer circuit board is developed to obtain desired current pulse and solenoid on time. The data acquire by the sensor is passed to the PC, for the subsequent analysis. Power Circuit Board used for this experiment, is designed keeping following considerations,

- On time of solenoid should never exceed more than 3 ms.
- Voltage and current rating should always with in permissible limit to avoid permanent damage of the solenoid coil.

To ensure this power supply circuit, through PWM controller current is kept within a fixed limit. For force measurement value of current and as well as the distance between solenoid tip and anvil has been varied. Here 3525 PWM controller is used for controlling the time pulse. Essentially, this PWM controller works on the pulse, by which it can control the timing circuit. This timer has its timing response between 2ms to 500ms provide an opportunity to vary the current inside the solenoid as further depicted in Fig 11.

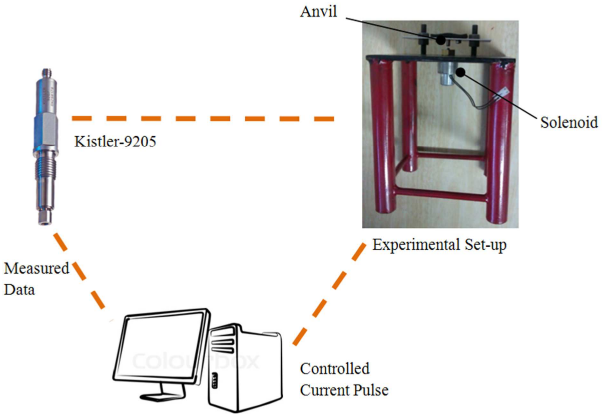


Fig. 10. Schematic plan for solenoid test set-up

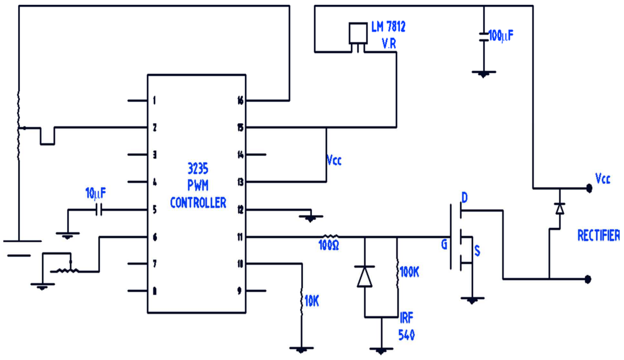


Fig. 12. Schematic of power supply kit

The potentiometer act as a controller to controls the timing delay. For current measurement, 0.9Ω resistance is used. The testing set up is shown in Fig.12.

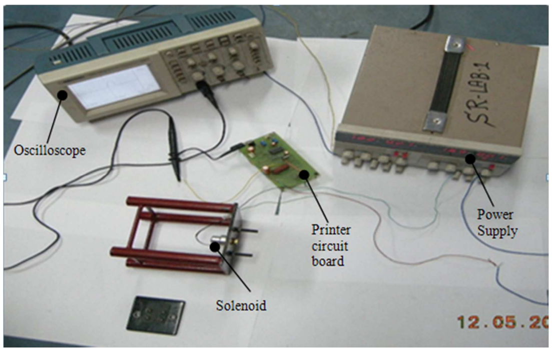


Fig. 13. Testing set up of solenoid with power circuit board

In order to investigate the influence of the thickness of anvil rubber, measurements are also taken on experimental setup. The results are shown in Fig.13. This study clearly shows that damping is most effective while using EPDM 80 shore hardness (Ethylene propylene diane monomer M-class rubber) with thickness 2.5 mm. The anvil rubber used earlier was made of natural rubber 40 shore hardness, which is a rather soft rubber. A print out test with the anvil rubber changed to 80 shore hardness found a more promising dot quality. A longer test was made with EPDM 80 shore hardness and it has been found that the length of the print out made almost no difference to print quality. Only minor and negligible difference could be seen with trained eye between the first and 50th page. A similar type of output quality has also been found in case natural rubber 70 shore hardness and EPDM 80 shore hardness. Only for large volume exceeding of 60 or more, a trained eye can detect deviation between EPDM 80 shore hardness & the natural rubber. Therefore EPDM 80 shore hardness has been chosen due to its excellent properties, which does not changed over the operating temperature range of 20°C to 60°C.The difference between a print out with natural rubber 40 shore behind the anvil and the EPDM 80 shore behind the anvil is shown in Fig. 14.

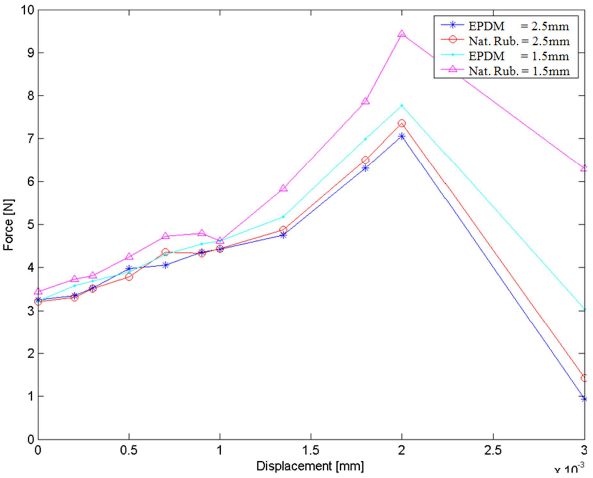


Fig. 14. Results from experimental setup with different type of rubber @ I_{coil} =2.7 Amp.

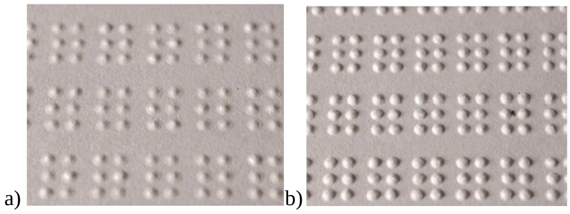


Fig. 15. a) Dots after 30 sheets print out with 40 shore hardness natural rubber
b) With EPDM 80 shore

This has resulted in selection of appropriate damping material to solve the problem of bad quality on the braille dots.

The next problem of quality of braille dots in waviness in printout due to vibration in the system. This limits the operating speed of the printer. To increase the operating speed an experimental setup is constructed as shown in Fig.15, to facilitate measurement of the vibration, produced by the reciprocation of the solenoids, movement of print-head over guide rod (Fig.5) and presence of stepper motors in the braille printing system . In this setup it is made possible to choose the shape and periodicity of the generated current pulse . An FFT analyzer "Vibexpert" was used for measuring vibration pattern. A desktop computer resident special purpose software converts the text into braille & subsequently generates a series of current pulse, that is passed to the solenoid system of the print head. The data acquired by the FFT analyzer is passed to the computer for the final analysis. The position of the measuring probe of the FFT analyzer can be changed enabling measurement of vibration at different point of the braille system.

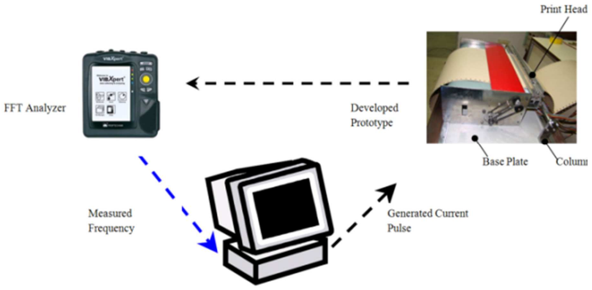


Fig. 16. Experimental setup for measurement of vibration in braille printer

Time domain vibration Analysis has been carried out as shown in Fig.16 on braille printer at various positions to gather information about system response. Here measurements are taken by changing the position of the measuring probe of the FFT analyzer, which is shown in Fig.17 and Fig.18.

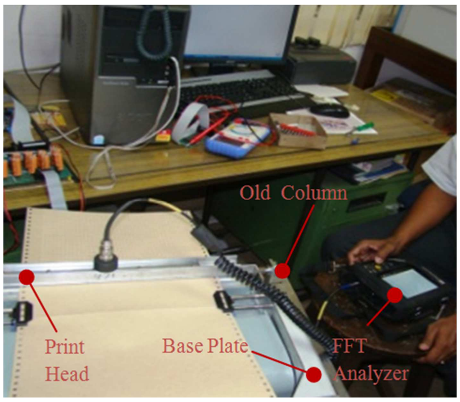


Fig. 17. Time domain vibration measurement

Stiffness of a structure is alternatively defined as the structural efficiency to transmit the loads applied on the structure to its supports, which helps to find a stiffer structure in design.

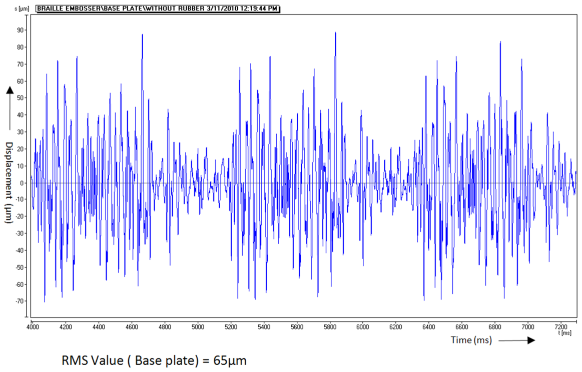


Fig. 18. Deflection of base plate

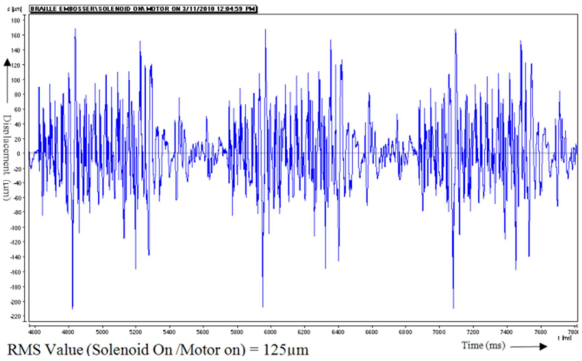


Fig. 19. Deflection of print head during printing

To minimize the vibration and thereby deflection support column design has been modified to incorporate more stiffness into the system as shown in Fig.19

Following are the main design parameters in earlier design

1) T shape mounting column as shown in Fig. 19a.
2) Bush and sleeve arrangement to facilitate attachment and detachment of guide road for ease of assembly and disassembly process of print head by simply detaching sleeve over bush as shown in Fig. 19a.

Though in the design assembly process of print head is very simple, but due to more no of assembly parts structural stiffness is less causing large vibration during printing as shown in Fig.17 and Fig.18.The analysis of time domain signal shows that the vibration is due to impulsive force generated by impact of the solenoid in print head during printing process.

To minimize the vibration new column design has been done ,which is having following design parameter

1) Square shaped mounting column as shown in Fig. 19b to increase cross sectional area.
2) Instead of bush and sleeve arrangement, upper portion of new column is modified to facilitate ease of assembly of guide rod. This arrangements are shown in Fig. 19b.

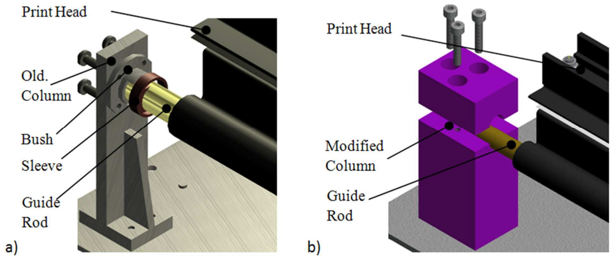


Fig. 20. a) Support column design with Bush and sleeve arrangmet b) Modified Design

This modification has improved stiffness of column due to reduce number of component or assembly parts and higher cross-section compared to the earlier one . The limitations on displacement and/or natural frequency of a structure specified in design codes actually require that the structure possess sufficient stiffness. Adding supports, reducing spans or increasing sizes of cross-sections of members can effectively increase structural stiffness [9]. After modification in column design various measurements are one again taken by changing the position of the measuring probe of the FFT analyzer. Results are shown in Fig.20 and Fig.21.

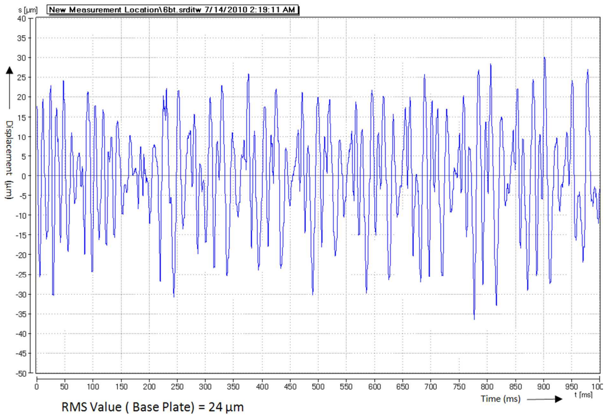


Fig. 21. Deflection of base plate (with modified column)

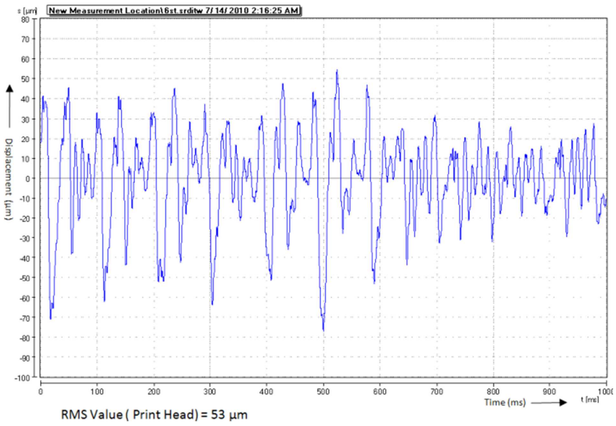


Fig. 22. Deflection of print head (with modified column)

This analysis clearly shows that by incorporating more stiffness into the system the print quality has been improved as well as vibration has been reduced considerably. The value of base plate deflection has now been reduced from 65 µm to 24 µm and at print head it decreased from 125 µm to 53 µm. By applying new insight & modified column it is possible to take print in both the direction showing reduction in vibration at an useful level. The print is also straight and without wavy nature which was a considerable improvement for bidirectional printing. Therefore we can conclude that rigidity of the mounting system plays an important criterion for reduction of vibration. The result is further depicted in the figure 23.

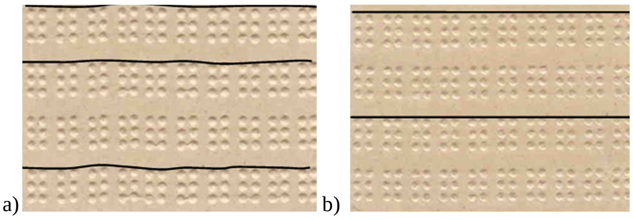


Fig. 23. a) Waviness in print
b) Straightness in print (Print-out with modified column)

4 Conclusion

This work has focused on theoretical, numerical and experimental approaches to achieve a comprehensive understanding of dynamical phenomena occurring in a complex electro-mechanical system, which uses impacts for generating braille output. The aim has been to show the usefulness of experimental driven approach for better understanding and optimizing the dynamic behaviour of products and thereby account for vibration and other mechanical parameter already present in the process. It has found that the variation of printing quality mainly depends on the anvil rubber used in the print head and solenoid tip profile. Braille print head, have been investigated in ADAMS$^{@}$ to conclude that impact modeling together with analysis tools can be used to investigate design problems and provide recommendations on how to improve well established dynamic modeling performance. The contact force has been analyzed by both analytically and through software using ADAMS$^{@}$. The main objective of this numerical work is to find-out parameters to guide a most suitable design for the system, which can provide a quality braille output. By experimentation it has been found that the thickness and hardness of anvil rubber is important to improve the quality of braille dots in long run.

The time domain vibration measurement has also been carried out to find out the inter relationship between printing and the printing speed. It has also been observed that stiffness at mounting column holds the key for better print quality. As a result column design has been changed to provide adequate stiffness resulting good quality print in both direction with reduced vibration to one third level. It is been also shown that when decreasing the time between subsequent excitation pulses (which is one way of increasing the printing speed), irregular behaviour can reappear. The system has been found to be sensitive to changes in velocity through which the impact mass is moving. Finally, this work shows that experiment driven product development approach is the key for modern electro-mechanical complex products design.

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