Numerical Modelling and Simulation of Dynamic Parameters for Vibration Driven Mobile Robot: Preliminary Study

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Abstract. The motion of vibration-driven robots is based on an internal oscillating mass which can move without legs or wheels. The oscillation of the unbalanced mass by a motor is translated into vibration which in turn produces vertical and horizontal forces. Both vertical and horizontal oscillations are of the same frequency but the phases are shifted. The vertical forces will deflect the bristles which cause the robot to move forward. In this paper, the horizontal motion direction caused by the vertically vibrated bristle is numerically simulated by tuning the frequency of their oscillatory actuation. As a preliminary work, basic equations for a simple off-centered vibration location on the robot platform and simulation model for vibration excitement are introduced. It involves both static and dynamic vibration analysis of robots and analysis of different type of parameters. In addition, the orientation of the bristles and oscillators are also analysed. Results from the numerical integration seem to be in good agreement with those achieved from the literature. The presented numerical integration modeling can be used for designing the bristles and controlling the speed and direction of the robot.

1. Introduction

For small and tiny crawling robots, vibration-driven mechanism is a suitable actuation system to be considered and implemented. Vibrational motion produced by periodic oscillations of internal masses is transformed into a directed locomotion. With increasing new applications in medical, manufacturing and maintenance, a greater demand for more efficient and reliable tiny robots are expected. This has created an interest to researchers to further enhance their understanding about vibration-driven robots for further improvement. For this purpose, numerical analyses and designs of vibration-driven robot for better motion and speed control were thoroughly studied [1-13].

Small vibration-driven robots are developed for different applications. The creation of different designs of mobile robots for movement through pipelines and similar technical systems can be found in [1]. An apedal locomotion system "Vibro-worm" to be used for inspection of pipelines was designed and tested. In another study [2], motion analysis, design and position control of a novel, low cost, sliding micro-robot which was actuated by centripetal forces generated by robot mounted vibration micro-motors was investigated. The micro-robot was able to perform translational and...
rotational sliding with sub-micrometer accuracy and develop velocities of up to 1.5 mm/s. Interestingly, [3] studied the Setaria viridis spike’s moving behaviour on vibrating cotton wire inspired from grass spike. The report claimed that the fabricated vibration-driven vehicle could move on a wide range of smooth and rough surfaces. In addition, research on the design, construction, performance and testing of a mechanical vibration exciter [4] concluded that the amplitude of vibration initially increases with increase in speed and reaches a maximum value (at resonance speed) and then decreases.

Analysis on the motion principle and behaviour of the vibration-driven robot also caught the attention of some researchers. For example, [5] investigated the performance of different friction models in microstick-slip motion systems, i.e. Coulomb, viscous, combined Coulomb and viscous model, Stribeck, Dahl, LuGre, and the elastoplastic friction models. The result showed that LuGre model had the best accuracy. Worked done by [6] proposed an efficient parameter estimation approach for LuGre friction model based on the chain-code method. In simulation studies, the locomotion behaviour of vibration-driven robot is frequently considered using a multibody system model. The aim is to obtain the influence of the system parameters on the motion behaviour [7], [8-9], and [10]. Research in [11] presented an analytical model and solved numerically for different configurations (direction of excitation) and parameters (length, bending stiffness, shape of the endpoint). The influence of vibration frequency on motion can be found in [12] and [13].

From the literature, it was found that the best parameters for vibrator position and the effect of bristle geometry are still vague. In this study, the changes in the motion behaviour when the parameter values are varied are observed numerically. As this study is still at the preliminary stage, the model has been simplified to ensure that the fundamentals of the model formulations are fully understood.

2. Numerical modeling
The numerical modeling of the vibration-driven robot is based on the prototype as in figure 1. The prototype consists of a rigid body with mass, \( m \) and length, \( L \). The oscillator is attached onto the main body either at the centre of mass or any other position along the main body for experimental purposes. The main body is supported with two bristles where the bristles can be changed to different sizes, shapes, slope angles and stiffness.

![Figure 1. Design of prototype for experiment.](image)

The oscillator is an eccentric rotating mass where the excitation force is created as in figure 2. The oscillator can be modelled as 1 DOF.
The rotation of the unbalanced mass creates the vertical, $f_V$ and horizontal, $f_H$ forces which can be derived as,

$$f_V = m_e \omega_e^2 \sin \theta_e$$  \hspace{1cm} (1)  
$$f_H = -m_e g - m_e \omega_e^2 \cos \theta_e$$  \hspace{1cm} (2)

where $m_e$ is the eccentric mass, $e$ is the eccentricity of rotating mass, $\omega_e$ is the rotation velocity of the motor, $g$ is the gravity acceleration and $\theta_e$ is the rotation angle of eccentric mass.

The vibration driven robot can be modelled as a 2-DOF platform as shown in figure 3.

The excitation force, $f_V$ can be positioned either at point $P_1$ or $P_0$. In this model, the damping factor is ignored and the centre of mass is assumed to be located at the centre of the platform. The equations of motion can be derived based on the energy method as,

$$T = \frac{1}{2} m \dot{\theta}_e^2, \hspace{1cm} (3)$$

$$V = \frac{1}{2} k_1 (y - L \theta_e)^2 + \frac{1}{2} k_2 (y - L \dot{\theta}_e)^2 \hspace{1cm} (4)$$

where $T$ is the total kinetic energy, $V$ is the total potential energy, $J_0$ is the moment of inertia, $\theta_e$ is the angle of rotation at centre of mass, $\dot{\theta}_e$ is the first derivative of angle of rotation with respect to time, while $k_1$ and $k_2$ are the stiffness of spiral spring. From the Lagrangian, we know that,

$$L = T - V \hspace{1cm} (5)$$

and Lagrange’s equations in the Cartesian coordinates can be derived as,

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}_e} \right) - \frac{\partial L}{\partial \theta_e} = Q_e \hspace{1cm} (6)$$
where \( q \) is the generalized coordinates and \( i \) is the number of the degree of freedom of the system. Therefore, equations (3) and (4) become as,

\[
m''x + (k_1 L_2 - k_2 L_1) \theta = f_x \\
J_\theta'' \theta + (k_2 L_1^2 - k_1 L_2) y + (k_1 L_2^2 + k_2 L_1^2) \theta = -f_\theta L_1
\]

Equation (7) and (8) can be written in the form of matrix as

\[
\begin{bmatrix}
m & 0 \\
0 & J_\theta
\end{bmatrix}
\begin{bmatrix}
v_1 \\
v_2
\end{bmatrix}
\begin{bmatrix}
y \\\n\theta
\end{bmatrix}
= \begin{bmatrix}
f_x \\
f_\theta L_1
\end{bmatrix}
\]

where equation (9) can be simplified into,

\[
[M]\{v\} + [K]\{y\} = [F]
\]

The horizontal displacement, \( x(t) \) can be calculated as

\[
x(t) = d \sin \left( \cos^{-1} \left( \frac{y_c - y(t)}{d} \right) \right) - d \sin \theta_b
\]

where \( d \) is the length of the bristles and \( \theta_b \) is the slope angle of the bristles. Equations (9) and (11) are integrated numerically based on the table 1 and table 2.

Table 1. Model parameters – Group 1.

| Descriptions         | Unit | Set A | Set B | Set C |
|----------------------|------|-------|-------|-------|
| Mass, \( m \)        | g    | 40    | 40    | 40    |
| Internal mass, \( m_e \) | g    | 2     | 2     | 2     |
| Eccentric, \( e \)   | mm   | 2     | 3     | 4     |
| Bristle length, \( d \) | mm   | 2     | 4     | 6     |
| Bristle angle, degree | \( \theta_b \) | 30    | 25    | 35    |
| Stiffness, \( k_1 = k_2 \) | Nm   | 10    | 100   | 1000  |
| Frequency, \( \omega_e \) | Hertz | 10    | 10    | 10    |
Table 2. Model parameters – Group 2.

| Descriptions          | Unit | Set A | Set B | Set C |
|-----------------------|------|-------|-------|-------|
| Mass, $m$             | g    | 40    | 40    | 40    |
| Internal mass, $m_e$  | g    | 2     | 2     | 2     |
| Eccentric, $e$        | mm   | 2     | 3     | 4     |
| Bristle length, $d$   | mm   | 2     | 4     | 6     |
| Bristle angle, $\theta_B$ | degree | 30   | 25   | 35   |
| Stiffness, $k_1,k_2$  | Nm   | 1,10  | 100,10 | 1000,10 |
| Frequency, $\omega_e$ | Hertz | 10   | 10   | 10    |

Table 3. Model parameters – Group 3.

| Descriptions          | Unit | Set A | Set B | Set C |
|-----------------------|------|-------|-------|-------|
| Mass, $m$             | g    | 40    | 40    | 40    |
| Internal mass, $m_e$  | g    | 4     | 6     | 8     |
| Eccentric, $e$        | mm   | 2     | 3     | 4     |
| Bristle length, $d$   | mm   | 2     | 4     | 6     |
| Bristle angle, $\theta_B$ | degree | 30   | 25   | 35   |
| Stiffness, $k_1,k_2$  | Nm   | 10,10 | 100,10 | 1000,1 |
| Frequency, $\omega_e$ | Hertz | 10   | 10   | 10    |

3. Results and discussion

Numerical parametric study is conducted to determine the dependency between the oscillator positions, the excitation force and bristles stiffness. The oscillator is placed at $P_1$ and the displacements at point $P_1$, $P_0$ and $P_2$ are observed. The results are given as in figure 4, figure 5 and figure 6.

From the results of figure 4, it is clearly shown that the oscillator position plays an important role to the robot motion. If the oscillator is placed at the centre of mass, the displacements for both bristles are the same. However, when the oscillator is placed at point $P_1$, the amount of displacement at each point are different and occurred at different phases for every time step. It shows that the displacement at the oscillator location is larger than at the other side of the robot platform.

![Figure 4. Bristles displacement at y-direction vs. time for table 1.](image-url)
Figure 5. Bristles displacement at y-direction vs. time for table 2.

Figure 6. Bristles displacement at y-direction vs. time for table 3.

From figure 5, we can see the changes of spring stiffness, $k_1$ from 1 Nm to 1000Nm (while $k_2$ remain the same) did not show any significant effect at Point 2, $P_2$ as it only shows the displacement of the bristle almost similar at $P_0$ and $P_1$.

Form figure 6, the change of excitation forces and spring stiffness as in set A and B did not show significant effect to the displacement. However, when there is huge different of stiffness value between two springs and increasing of internal mass as in Table 3 – Set C, the phase of displacement sine wave for each point $P_1$, $P_2$ and $P_3$ started to decrease and close each other. Therefore, it can be said the time of force transmission between two points decrease when using different value of spring stiffness for each bristle.

In general, the stiffness of the bristles also affected the displacement of the bristles where high stiffness will reduce the bristle displacement and vice versa. On the other hand, low stiffness could reduce the spring response and hence will slow down the horizontal speed of the robot.

### 4. Conclusions

The numerical analysis conducted on the dynamic model of the vibration-driven robot shows that the displacements of the vibration-driven robot are affected by the position of the oscillator, the excitation force and the stiffness of the bristles. Adjusting the values of these crucial variables will cause different motion behaviours. Thus, it can be used as a consideration factor in designing an effective vibration-driven robot.

From the preliminary results, it can be said the best position for excitation force should be located at the end of the platform while the bristles stiffness did not produced significant influence to the displacement and velocity of the robot.

In conclusion, it can be said that to fully understand the motion behaviour of vibration-driven robots, the numerical dynamic model analysis should consider the effect of varying other parameters
such as the damper characteristic of the bristles, geometric parameters of the bristles, and friction forces to make the motion more realistic.

References

1. V. Lysenko, K. Zimmermann, A. Chigarev, F. Becker, 2011, 56th International Scientific Colloquium, Ilmenau University of Technology.
2. P. Vartholomeos, E. Papadopoulos, 2006, IEEE International Conference on Robotics and Automation, 649-654.
3. S. Bai1, Q. Xul, Y. Qin, 2013, Sci. Rep. 3.
4. N. Anekar, V.V. Ruiwale, S. Nimbalkar, P. Rao, 2014, IJRET, 03, Issue: 08.
5. Y. F. Liu, J. Li1, Z. M. Zhang, X. H. Hu, and W. J. Zhang, 2015, Mech. Sci., 6, 15–28.
6. B.X. Liu, S.H. Nie, 2015, The 14th IFToMM World Congress.
7. F. Becker, 2015, IF’AC, 48-1, 842–843.
8. L. Giomi, N. Hawley-Weld, L. Mahadevan, 2013, Proc. R. Soc. A 2013 469.
9. T. Al Ahmadi, A. Al Shamardi, N. Alotibi, 2016, ME 4773/5493 Fundamental of Robotics.
10. F. Becker, V. Lysenko, V. Minchenya, I. Zeidis, K. Zimmermann, 2013, Springer, 8-3, 299-306.
11. F. Becker1, S. Börner, V. Lysenko, I. Zeidis, K. Zimmermann, 2014, ISR Robotik, ISBN 978-3-8007-3601-0.
12. G. Cicconofri, F. Becker, G. Noselli, A. DeSimone, K. Zimmermann, 2016, ROMANSY 21 - Robot Design, Dynamics and Control, 569, 225-232.
13. G. Cicconofri, A. DeSimone, 2015, IJNLM, 76, 233-239.