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Effect of Vibrator Parameters and Physical Characteristics of Parts on Conveying Velocity

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Automation is generally employed in the area of orienting, lifting, and moving parts for production in industries including automotive, electronic, food, and packaging. With the help of automation, it is possible to reduce the manufacturing time and labour required. The most adaptable tools for feeding small, designed pieces during part assembly are vibratory feeders. Industries have been effectively using vibratory feeders for more than 30 years, indicating that such technology is advanced. Although research in this area has not been lacking, a fundamental understanding of the interactions between a part's physical characteristics and the various vibratory feeder operating parameters in relation to optimal performance, defined as conveying a part with maximum stability and maximum velocity, remains lacking in linear feeders. While several papers discuss the effect of vibratory parameters (excitation frequency and amplitude of vibration) and the coefficient of friction, the effect of characteristics of part (l/w ratio and mass) is neglected. In this work, the effect of these factors on the conveying velocity of prismatic parts made of aluminium and brass on a horizontal track without inclination was determined, and an attempt was made to develop a predictive model based on the above factors. Using Taguchi's design of experiments (DOE), an L16 orthogonal array was designed. A response table for the signal-to-noise ratio has yielded optimal values for each parameter taken into consideration. ANOVA predicted frequency as the most influential parameter, followed by the coefficient of friction. The regression analysis yields an R^2 value of 99.3 % for aluminium and 98.7 % for brass. The results of the regression model and random experiments show a high correlation of 91.66 %. This model is required to set the desired conveying velocity of parts so that continuous flow can be maintained in automated assembly or packaging industries.
Keywords: linear vibratory feeders, conveying velocity, mass, l/w ratio, coefficient of friction

Highlights
- *Vibratory feeders are commonly used for conveying small components in automated assembly lines. Controlling its conveying velocity by controlling its parameters will enable the smooth execution of the assembly process.*
- *This paper is an attempt to study the effect of parameters such as excitation frequency (f), the amplitude of vibration (A), the mass of part (m), length-to-width ratio (l/w) and coefficient of friction (μ) between the part and vibrator, on the conveying velocity (v) of the vibratory feeder.*
- *Though several research studies have examined the behaviour of frequency, amplitude and coefficient of friction, the effect of the physical characteristics, such as the mass of part (m) and length-to-width ratio (l/w,) have not been studied earlier with reference to linear vibrators.*
- *ANOVA results show that the percentage of the contribution of the physical characteristics to the conveying velocity is also significant.*

0 INTRODUCTION

The world was forever altered by the introduction of assembly line technology. Previously, a single operator handled the entire assembly of a product. This required each operator to become proficient in numerous separate specialities, which led to extended apprenticeships and low total output levels. Numerous developers were inspired by Evans [1] notion of transporting goods from one location to another without the need for manual labour and adopted it as their own. With even basic automation came improvements in part quality, efficiency through quicker cycle times, yield (less rework and scrap), labour costs, and worker safety. Specialized assembly equipment is typically too expensive for small-scale and medium-scale manufacturing businesses. Flexible automatic assembly methods are employed as an alternative. These systems have the benefit of being reprogrammable, allowing the machine to be set up to execute the sequential processing of the product. Changing the system's programming typically entails reconfiguring the manipulator and the feeding system's parts feeders. Retooling for alternate manufacturing can take up much time and money; therefore, parts feeders, which were frequently retooled during product changes, required considerable knowledge on the part of the manufacturer.

A part feeder is a device that accepts a number of erratically oriented parts at its input and conveys parts in a specific orientation at its output and is divided into non-vibratory and vibratory feeders based on the motive force. Non-vibratory parts feeders are generally exclusive and employed in long production

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run scenarios. A vibratory feeder is an instrument in which vibration is the mode of actuation to feed material to a process or machine. Vibration as a means of conveyance can be achieved by throwing the material to be transferred at a micro-level [2]. Gravity and vibration are both used by vibratory feeders to move material. Vibration is applied to move the material, while gravity is used to set the direction. They are mostly employed for the transportation of numerous small components. Vibratory feeders are of two types.

- vibratory bowl feeder (VBF) and
- linear vibratory feeder.

Literature based on the performance and functioning of vibratory bowl feeders, which deal with studying the jump-less and jump-type conveyance related to amplitude variation [3], calculation of natural frequencies [4], natural resting aspects of parts [5], analysing the feeding and orienting of small parts and flexible part feeding of small components in automation [6], force analysis [7], and simulation of part motion [8].

In a linear feeder, the feeder assembly is a dynamically balanced, two-mass vibrating system whose actuation is by electromagnetic means. This system consists of a trough, which is connected to an electromagnetic drive through leaf springs. Fig. 1 shows a linear vibratory feeder model considered for the study. Like bowl feeders, linear vibratory feeders and their functioning, performance [9] and [10], motion analysis [11] and [12], dynamic modelling [13], analysis on feeding, orienting, conveying small parts without sensor feedback [14] and [15], mathematical modelling of resonant vibratory feeder [16] and [17], and control of the vibrator [18] are also dealt with in literature.

Feeders are the most significant components in an automation system; if the conveying velocity of these feeders could be controlled by directing the factors, then many automated systems could be programmed easily. Several studies focus on the velocity of parts moving on a vibrator and the factors that influence the conveying velocity. A detailed description of the effect of frequency, amplitude and coefficient of friction was given by Boothroyd [19]. Ramalingam and Samuel [20] discussed the behaviour of linear vibratory feeders and the measured values of velocity, which were in good agreement with experimental studies. Frequency, track angle and amplitude of vibration were considered. Sloot and Kruyt [21] have presented theoretical and experimental studies on transporting granular material in both slide and flight conveyors with varying inclinations of the track. The influence of the inclination of the track, throw number, coefficient of friction and vibration angle on the velocity efficiency was studied. The theoretical and experimental results agreed satisfactorily for slide conveyors and varied for flight conveyors. Okabe et al. [22] discussed how friction characteristics behave in a newly developed vibratory feeder.

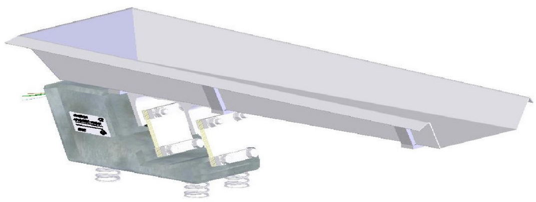

Fig. 1. *Linear vibratory feeder model*

Lim [23] made a dynamic analysis of a vibratory feeder and concluded that the factors that could affect the rigid body's conveying velocity are the vibration angle, the amplitude of vibration, the coefficient of friction, the inclination of the plate and the operating frequency. Wolfsteiner and Pfeiffer [24] used an oscillating track with frequencies up to 100 Hz. In this paper, a complete mechanical model of part feeding dynamics based on unilateral constraints with Coulomb friction was discussed. Kawachi et al. [25] proposed an algorithm for simulating simultaneous collision impulses with friction between rigid bodies.

Based on the literature survey, it was found that significant work has not been carried out in determining the conveying velocity considering the physical characteristics of the part, such as the *l*/*w* ratio and mass. This paper fills that gap by considering parts made of brass and aluminium. Brass is mainly used in the field of door hinges, utensils, electrical appliances, pipeline fittings, etc., while aluminium is mainly used in the fields of aerospace, automotive, marine, rail, building construction, energy distribution etc. Models with appropriate *l*/*w* ratios and mass have been manufactured for experimental studies. The objective of this research work is to determine the effect of the following factors on the conveying velocity of the part:

- vibrator parameters - excitation frequency (f) and amplitude of vibration (A),
- physical characteristics of mass of part (m), length-to-thickness ratio (l/w) and
- coefficient of friction (μ) between the part and vibrator.

The track angle/inclination is not considered since it is a horizontal vibratory feeder. To reduce the number of experiments and find the most significant parameter among the vibrator parameters and physical characteristics of parts, a Taguchi design of experiments and ANOVA methods are used [26].

1 SELECTION OF LEVELS OF FACTORS

To satisfy the objective, the following methodology is proposed:

- Fix the levels of mass of the part and length-to-width ratio (*l*/*w*) and manufacture them.
- Conduct a pilot study to determine the levels for the factors excitation frequency (*f*), the amplitude of vibration (*A*), the mass of part (*m*), the length-to width-ratio (*l*/*w*), and the coefficient of friction (μ) between the part and feeder, for conducting the actual experiments.
- Experimentally determine the effect of the factors on the conveying velocity.
- Determine the most significant factor using ANOVA.
- The method of selection of levels is discussed below. A pilot study to determine the values of the frequency and amplitude of vibration of the feeder was conducted.

1.1 Determining the Excitation Frequency and Amplitude of Vibration

By trial and error, the frequency between 10 Hz to 50 Hz was chosen because, no appreciable movement of parts was observed in the vibratory feeder below 10 Hz and above 50 Hz. The frequency was chosen at equal intervals between 10 Hz to 50 Hz at four levels: 15 Hz, 25 Hz, 35 Hz, and 45 Hz. The Vibrodyne controller has a phase angle control system, which helps vary the voltage and, consequently, the vibration amplitude of an electromagnetic feeder. Vibration amplitude is varied by varying the input voltage (% of the input voltage) of the electromagnetic feeder as per the specifications given in Table 7. Amplitude was chosen between 65 % and 90 % of input voltage, because below 65 % there was no appreciable movement of part in the feeder, and very high decibel noise was observed above 90 % of input voltage. Similar to the frequency, the amplitude was also chosen at equal intervals between 65 % to 90 % of input voltage at four levels (75 %, 80 %, 85 % and 90 % of input voltage), as better velocities were obtained at this range during trials.

The factors and levels chosen for the experimental studies for aluminium and brass are shown in Tables 1 and 2, respectively.

1.2 Determining the *l*/*w* ratio and mass of the part

Parts chosen are to be commonly used parts in industries and therefore, prismatic parts made of aluminium and brass were considered for the experimental studies. Four parts with masses of 50 g, 100 g, 150 g and 200 g with a thickness of 6 mm were chosen for experimental studies. The *l*/*w* ratio was fixed at four levels (1, 1.5, 2, and 2.5). Hence, 16 workpieces were manufactured in aluminium, as shown in Fig. 2 and brass as in Fig. 3, satisfying the above conditions; the values are given in Tables 3 and 4, respectively.

Table 1. *Factors and levels chosen for aluminium*

Factors	Levels			
	I	II	III	IV
Excitation frequency [Hz]	15	25	35	45
Amplitude of vibration [% of input voltage]	75	80	85	90
Coefficient of friction (μ)	0.290	0.320	0.317	0.572
l/w ratio	1.0	1.5	2.0	2.5
Mass [g]	50	100	150	200

Table 2. *Factors and levels chosen for brass*

Factors	Levels			
	I	II	III	IV
Excitation frequency [Hz]	15	25	35	45
Amplitude of vibration [% of input voltage]	75	80	85	90
Coefficient of friction (μ)	0.331	0.419	0.445	0.629
l/w ratio	1.0	1.5	2.0	2.5
Mass [g]	50	100	150	200

Table 3. *Dimensions of aluminium work piece*

S. No	l/w ratio	Mass [g]	Length [mm]	Width [mm]
1	1	50	56	56
2	1	100	79	79
3	1	150	96	96
4	1	200	111	111
5	1.5	50	68	45
6	1.5	100	96	64
7	1.5	150	119	79
8	1.5	200	136.5	91
9	2	50	80	40
10	2	100	112	56
11	2	150	136	68
12	2	200	158	79
13	2.5	50	87.5	35
14	2.5	100	125	50
15	2.5	150	152.5	61
16	2.5	200	175	70

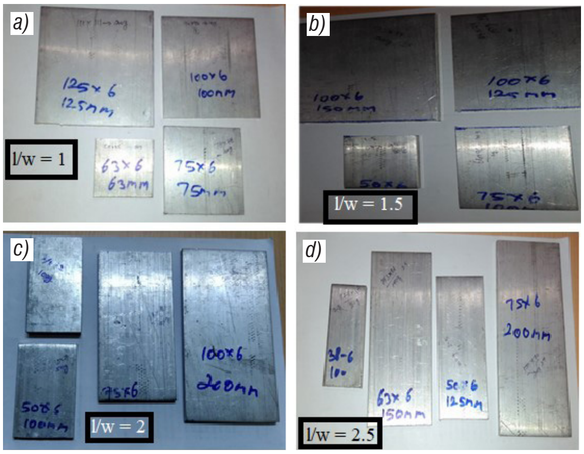

Fig. 2. *Aluminium parts with varying l/w ratio;*
a) l/w = 1, b) l/w = 1,5, c) l/w = 2, and d) l/w = 2,5

Fig. 3. *Brass parts with varying l/w ratio;*
a) l/w = 1, b) l/w = 1,5, c) l/w = 2, and d) l/w = 2,5

Table 4. *Dimensions of brass work piece*

S. No	l/w ratio	Mass [g]	Length [mm]	Width [mm]
1	1	50	30	30
2	1	100	42	42
3	1	150	51	51
4	1	200	59	59
5	1.5	50	36	24
6	1.5	100	51	34
7	1.5	150	63	49
8	1.5	200	72	48
9	2	50	42	21
10	2	100	60	30
11	2	150	72	36
12	2	200	84	42
13	2.5	50	47	19
14	2.5	100	66	26
15	2.5	150	81	32
16	2.5	200	93	37

1.3 Determining the coefficient of friction

To vary the coefficient of friction μ, different track materials are used. The materials other than stainless steel are:

- rubber sheet,
- polythene sheets, and
- black chart.

The stainless-steel tray of the feeder was wrapped with materials (i.e., polythene sheet, black chart and rubber sheet) to vary the coefficient of friction. The coefficient of friction was obtained through the reciprocating friction monitor (RFM) equipment. RFM is an apparatus used to measure the dynamic coefficient of friction of materials under a reciprocating sliding motion.

The base plate of dimension 30 mm × 30 mm × 6 mm is fixed at the bottom and the pin of diameter 4 mm and length of 10 mm is allowed to pass over the base plate. The coefficient of friction values obtained using RFM equipment are listed in Table 5.

Table 5. *Coefficient of friction values*

Part material	Track material			
	Polythene	Stainless steel	Black chart	Rubber sheet
Brass	0.290	0.320	0.317	0.572
Aluminium	0.331	0.419	0.445	0.629

2 EXPERIMENTAL SETUP

The linear vibratory feeder and controller used for experimentation is described below.

2.1 Electromagnetic Part Feeder

The part feeder considered for the experimental studies to determine the effect of vibrator parameters (excitation frequency, amplitude of vibration, track angle), physical characteristics of the part (weight, length to thickness ratio) and coefficient of friction between the part and feeder on conveying velocity of part is LF02 shown in Fig. 4 and the specification is shown in Table 6. The LF02 feeder assembly is a dynamically balanced, two-mass vibrating system whose actuation is by electromagnetic means. This system consists of a trough, which is connected to an electromagnetic drive through leaf springs. Fig. 4 shows the vibratory part feeder with stainless steel track. The electromagnetic drive consisting of a coil and core assembly is located inside the base housing. This assembly is connected to the backside of the drive unit housing. An armature is also a part of the drive unit and is placed opposite to the core and coil and is connected to the trough mounting bracket. Leaf springs are located at the front of the drive unit housing and are clamped to the drive unit housing and to the trough mounting bracket at the bottom and the top. Fig. 5 shows a block diagram of a linear vibratory feeder, which represents the amplitude and frequency: the vibrator's parameters, varied using the controller without feedback, and the part's physical characteristics considered for the study.

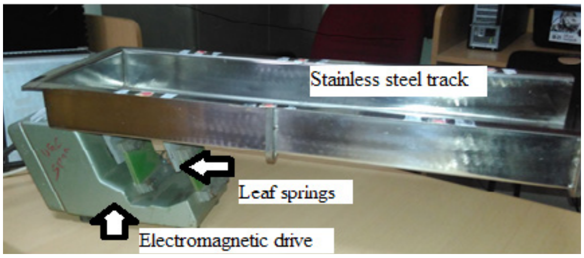

Fig. 4. *Vibratory part feeder with stainless steel track*

Table 6. *Specification of vibratory feeder*

Description	Details
Model	LF 02
Made	HVPL
Frequency range	200 Hz
Track	Stainless steel
Dimension of track (l×w)	600 mm × 180 mm

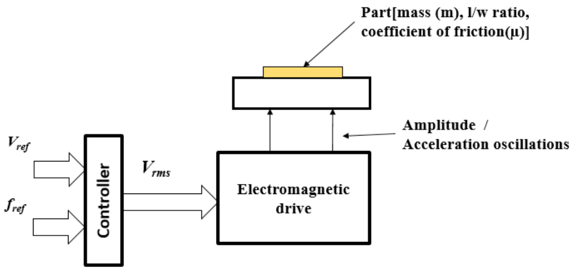

Fig. 5. *Block diagram of an electromagnetic vibratory feeder*

2.2 Feeder Controller

Vibrodyne is a controller for controlling any electromagnetic feeder in the processing and packing industry. Fig. 6 shows the variable frequency variable voltage electromagnetic feeder controller. It has been designed with a 32-bit controller which has:

- a feed rate from 0 % to 100 %,
- non-volatile memory,
- programmable ramp up and ramp down option,
- interacts with PLCs and other automation components in the system.

Table 7 provides the specification of the vibratory feeder controller that was used to control the excitation frequency and amplitude of vibration. The amplitude of vibration is controlled by means of variable voltage.

Table 7. *Specification of feeder controller*

Description	Details
Controller make	Vibrodyne
Frequency range	10 Hz to 200 Hz
Amplitude	10 % to 100 % of output voltage

3 DESIGN OF EXPERIMENTS

The method of design of experiments (DoE) was considered to conduct the experiments on the vibratory part feeder. Taguchi's design **[26]** to **[29]** is used to avoid the extensive experimentation. Five factors and four levels were determined for the experimental studies for which Taguchi suggests an L16 orthogonal array.

4 EXPERIMENTAL STUDIES

The experiment was conducted based on the L16 Taguchi Orthogonal array. The steps followed are described as follows. The vibratory feeder was switched ON. The frequency and amplitude of vibration were set to determined values in the controller. The START button was pressed in the controller, and the parts moved in the part feeder. Experiments were conducted based on the L16 orthogonal array to determine the conveying velocity as the response. The initial and final distances were marked in the vibratory part feeder. As soon as the parts touch the initial line, the timer was switched ON; when the parts touched the final line, the timer was switched OFF. The distance between the initial and the final line is 400 mm. For each part, the trial was conducted five times, based on which the mean time was calculated. Finally, the conveying velocity was obtained by calculating the ratio between the distance travelled by the part and the measured time taken for the part to travel between the initial and final lines. To vary the coefficient of friction, three different sheets (e.g., polythene, black chart, and rubber sheet) are placed on the vibratory part feeder, and the same procedure was repeated. The observations were recorded and presented as follows.

Fig. 6. *Vibrodyne controller*

4.1 Effect of Frequency on Conveying Velocity

Based on the experimental results, a graph is plotted between Frequency and Velocity for both brass and aluminium of mass 50 g, and 200 g and an l/w ratio of 1 as shown in Figs. 7 and 8.

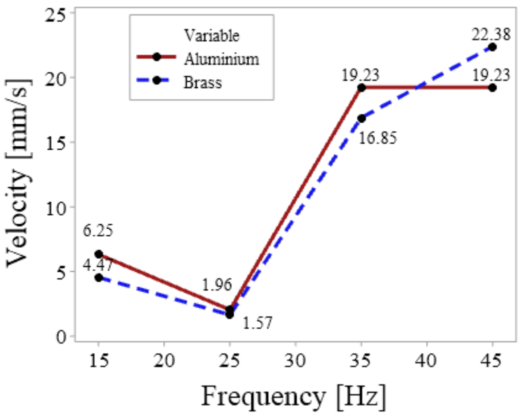

Fig. 7. *Effect of frequency on conveying velocity (m = 50 g, l/w = 1)*

At the frequency of 15 Hz, the velocity is 6 mm/s, as the cycles per second is low, and the parts have enough time to grip onto the track to move forward. It reduces intermittently when it reaches the frequency of 25 Hz. The velocity again increases at 35 Hz and is maximum at the frequency of 45 Hz for both aluminium and brass parts because they tend to jump rapidly to move forward. The effect of the frequency on the conveying velocity is highly non-linear.

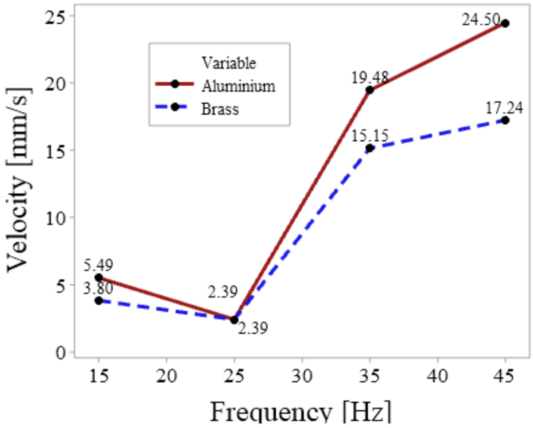

Fig. 8. *Effect of frequency on conveying velocity (m = 200 g, l/w = 1)*

4.2 Effect of Mass on Conveying Velocity

The variation of conveying velocity with respect to mass at constant frequency, amplitude and l/w ratio is shown in Fig. 9 (f = 15 Hz, A = 75 % of voltage and l/w = 1.5). It shows the behaviour of parts of different masses (50 g, 100 g, 150 g, and 200 g) with an l/w ratio of 1.5; the frequency is set at 45 Hz, and the amplitude is set at 90 % of the input voltage in the controller. The vibrator is started, and the time taken for each component to travel the distance from the start to finish lines is measured using a timer. The velocity is then calculated by finding the ratio of distance travelled by time taken.

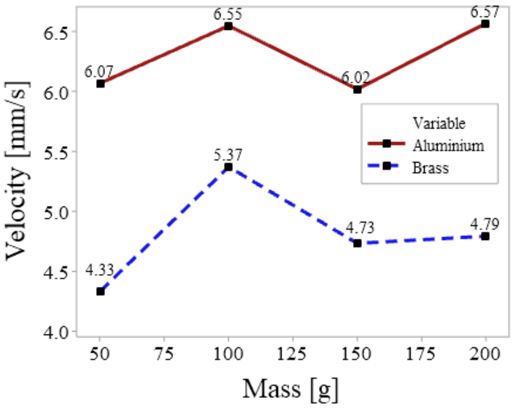

Fig. 9. *Effect of mass on conveying velocity (f = 15 Hz, A = 75 % of voltage and l/w = 1.5)*

From the graph (Fig. 9), it is clear that both aluminium and brass follow the same pattern for velocity. Velocity is low for 50 g mass, while it increases for 100 g again sweeps down at 150 g and increases for 200 g. Velocity is higher when the mass is 100 g and 200 g, compared to when the mass is 50 g and 150 g. Similarly, Fig. 10 shows the effect of mass at a different frequency and amplitude but for the same l/w ratio (f = 45 Hz, A = 90 % of voltage and l/w = 1.5). The results are different from the previous graphs due to the change in frequency as well as amplitude. It is clear that the velocity decreases when the mass is increased for a lower frequency and amplitude. Velocity increases in another instance where the frequency and amplitude are higher. Therefore, based on these studies, it can be concluded that the effect is highly non-linear.

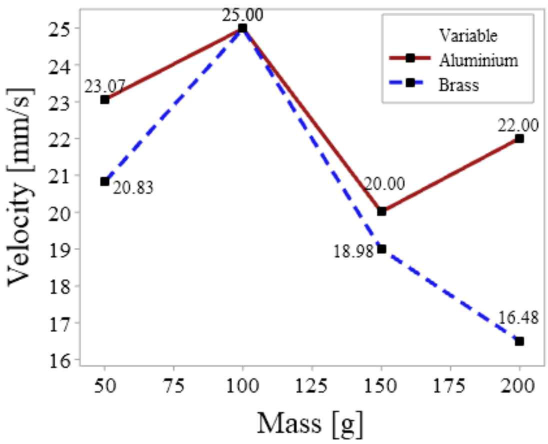

Fig. 10. *Effect of mass on conveying velocity (f = 45 Hz, A = 90 % of voltage and l/w = 1.5)*

4.3 Effect of l/w ratio on Conveying Velocity

The variation of conveying velocity with respect to l/w ratio at constant frequency, amplitude, and mass (f = 15 Hz, A = 75 % of voltage and m = 50 g) is, as shown in Fig. 11. In order to study the behaviour, the amplitude and frequency have been varied for the same mass and is as shown in Fig. 12 (f = 25 Hz, A = 80 % of voltage and m = 50 g). From the graphs (Fig. 12), it is clear that aluminium and brass parts follow the same pattern of velocity; velocity is maximum when the length is twice its width. The highest velocity for both aluminium and brass is attained at an l/w ratio of 2.0 irrespective of the change in amplitude and frequency. The effect of the l/w ratio on conveying velocity is again non-linear.

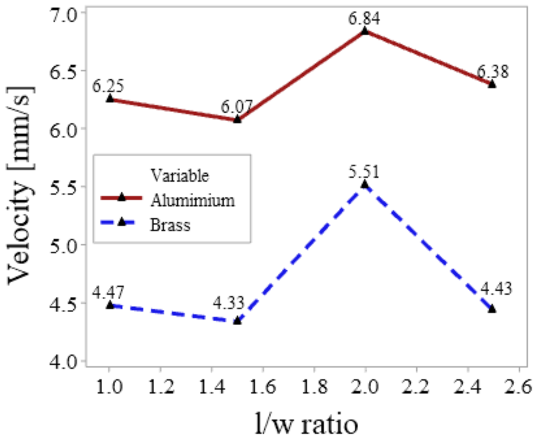

Fig. 11. *Effect of l/w ratio on conveying velocity (f = 15 Hz, A = 75 % of voltage and m = 50 g)*

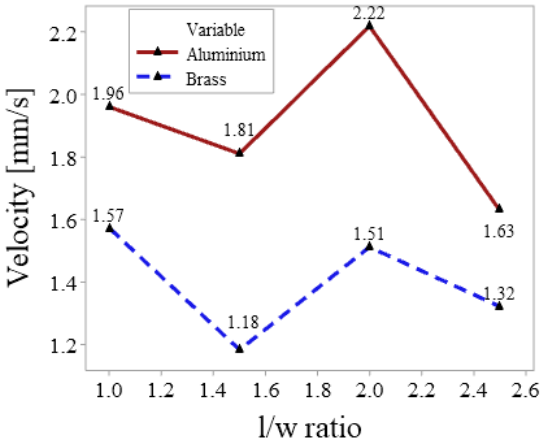

Fig. 12. *Effect of l/w ratio on conveying velocity (f = 25 Hz, A = 80 % of voltage and m = 50 g)*

4.4 Effect of Coefficient of Friction on Conveying Velocity

The frequency, amplitude, mass, and l/w ratio are maintained constant, and the graph is plotted between varying coefficient of friction and conveying velocity for both aluminium and brass; the experimental results are as shown in Fig. 13 (f = 45 Hz, A = 90 % of voltage, m = 50 g and l/w = 1.5) and Fig. 14 (f = 35 Hz, A = 85 % of voltage, m = 50 g and l/w = 1).

Irrespective of the change in frequency, amplitude, l/w ratio and constant mass, the pattern of behaviour of the conveying velocity is the same. Both tracks with lower and higher coefficients provide higher conveying velocity when compared with intermediary values of coefficients of friction. The effect of the coefficient of friction on the conveying velocity is also non-linear.

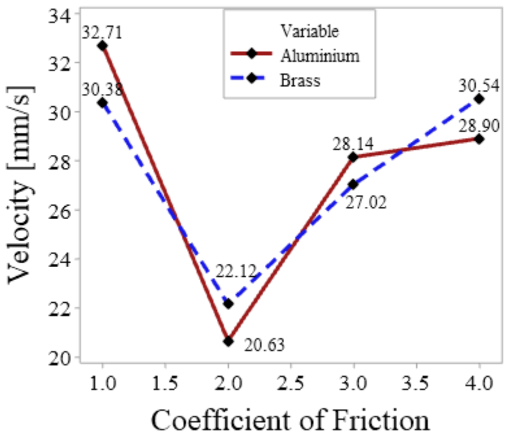

Fig. 13. *Effect of coefficient of friction on conveying velocity (f = 45 Hz, A = 90 % of voltage, m = 50 g and l/w = 1.5)*

From Fig. 14, it is clear that the rubber sheet, which has a higher co-efficient friction, has higher velocity and is closely followed by black chart. Polythene sheet, which has lower co-efficient of friction, provides higher velocity than stainless steel. Developing an analytical model is difficult as the observations are nonlinear. Hence, a predictive model called "regression analysis" was conducted to determine the conveying velocity.

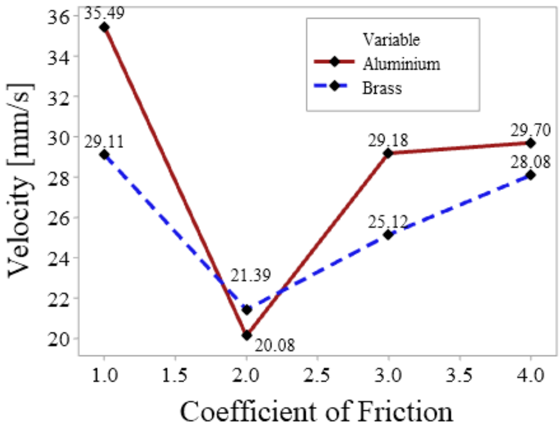

Fig. 14. *Effect of coefficient of friction on conveying velocity (f = 35 Hz, A = 85 % of voltage, m = 50 g and l/w = 1)*

5 REGRESSION ANALYSIS FOR DETERMINING CONVEYING VELOCITY

Regression analysis is a statistical tool that helps to find a quantitative association between independent and dependent variables. Simple linear regression helps fit a straight line for X and Y data points, with the goal of finding the line that best predicts the value of Y from X. Multiple Linear Regression model is tried in this paper to calculate the output (conveying velocity) with the set of input parameters (excitation frequency (f), amplitude of vibration (A), mass of part (m), length-to-thickness ratio (l/w), and coefficient of friction (μ) between the part and feeder). In fact, it creates the equation in which the values are entered to find out the desired output [27] to [30]. The regression equation was obtained by using Minitab 17 software. The regression equation for aluminium and brass are given in Eqs. (1) and (2), respectively.

For aluminium,

$$\begin{aligned} v = &-172.4 + 13.86\,f + 0.3344\,A + 272.3\,\mu \\ &+ 38.93\,l/w - 0.1329\,m - 0.08167\,f{\times}A \\ &- 3.830\,f{\times}\mu - 1.616\,f{\times}l/w - 0.02339\,f{\times}m \\ &- 1.625\,A{\times}\mu + 0.08481\,A{\times}l/w + 0.007848\,A{\times}m \\ &- 53.94\,\mu{\times}l/w - 0.09394\,\mu{\times}m \\ &+ 0.02844\,l/w{\times}m\,, \end{aligned} \tag{1}$$

$R^2 = 99.3$ % ,

For brass,

$$\begin{aligned} v = &\ 135.8 + 1.527\,f - 2.377\,A - 4.031\,\mu \\ &- 17.02\,l/w - 0.2810\,m + 0.000907\,f{\times}A \\ &+ 0.2308\,f{\times}\mu - 0.8903\,f{\times}l/w - 0.004218\,f{\times}m \\ &+ 0.9629\,A{\times}\mu + 0.7603\,A{\times}l/w + 0.005144\,A{\times}m \\ &- 59.15\,\mu{\times}l/w - 0.06450\,\mu{\times}m \\ &- 0.01271\,l/w{\times}m\,, \end{aligned} \tag{2}$$

$R^2 = 98.7$ % ,

where, R^2 is the percentage of total variation that could be explained by the regression equation, v conveying velocity [mm/s], f excitation frequency [Hz], A amplitude of vibration [% of input voltage], μ coefficient of friction between the tray and the material, l/w length to width ratio, and m mass [g].

5.1 SN Ratio

In Taguchi designs, a measure of strength is used to identify control factors that reduce inconsistency in a product or process by reducing the effects of uncontrollable factors (noise factors). Process parameters that can be controlled are called the "control factors". Parameters that cannot be controlled during production or product use are called "noise factors", but these can be controlled during experimentation. In a Taguchi-designed experiment, optimal control factor settings are identified that make the process or product strong, or resistant to variation. Higher values of the signal-to-noise ratio (SN) help identify control factor settings that reduce the effects of the noise factors.

Taguchi experiments use an optimization process with two steps. Step 1 identifies those control factors that reduce inconsistency. For this, the signal-to-noise ratio is used. Step 2 identifies control factors that move the mean to the target. This has a small or no effect on the signal-to-noise ratio.

The signal-to-noise ratio quantitates the responses relative to the nominal or target values for various noise conditions. Minitab offers four signal-to-noise ratios. In this analysis, the larger-is-better condition is chosen as the objective is to maximize the output response (i.e., conveying velocity). The mean effects plot for the SN ratio of aluminium is shown in Fig. 15.

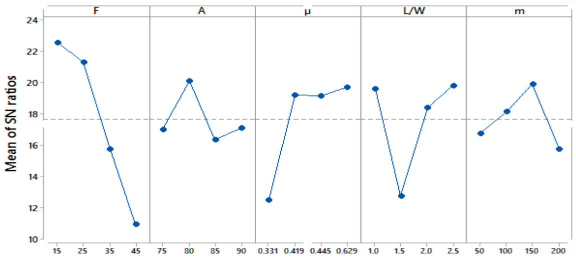

Fig. 15. *SN ratio for aluminium*

Table 8. *Response table for aluminium parts*

Level	f	A	μ	l/w	m
1	22.57	17.04	12.50	19.63	16.80
2	21.32	20.13	19.22	12.79	18.71
3	15.79	16.37	19.19	18.42	19.94
4	10.97	17.12	19.74	19.82	15.75
Delta	11.59	3.76	7.24	7.03	4.19
Rank	1	5	2	3	4

From the response table shown in Table 9 for aluminium, the optimal values of each factor that tend to maximize the conveying velocity could be determined by comparing the values in Tables 8 and 1 for aluminium parts. Maximum conveying velocity (v) for aluminium is obtained at a frequency (f) of 15 Hz, amplitude (A) of 80 % of input voltage, coefficient of friction (μ) of 0.629, l/w ratio of 2.5 and mass (m) of 150 g. The ranking also clearly indicates that the frequency is the most important factor that is influencing the conveying velocity followed by co-efficient of friction, l/w ratio, mass, and amplitude. The mean effects plot for SN ratio of brass is shown in Fig. 16. As per the response Table 9 and factors Table 2, maximum conveying velocity (v) for brass is obtained at a frequency (f) of 15 Hz, amplitude (A) of 90 % of input voltage, coefficient of friction (μ) of 0.290, l/w ratio of 1.0 and mass (m) of 200 g.

Table 9. *Response table for brass parts*

Level	f	A	μ	l/w	m
1	23.85	14.57	19.09	20.84	11.53
2	20.82	17.88	18.71	16.36	17.11
3	12.75	17.44	15.95	15.78	19.07
4	10.73	18.26	14.40	15.17	20.44
Delta	13.12	3.70	4.70	5.68	8.91
Rank	1	5	2	3	4

5.2 Analysis of Variance

Analysis of variance (ANOVA) is a group of statistical models used to explore the differences between group means and the procedures related to them (such as "variation" among and between groups), developed by Fisher **[31]** and **[32]** to **[35]**. ANOVA is used to study the effect of the factors which affect the conveying velocity.

The five input parameters are excitation frequency (f), amplitude of vibration (A), co-efficient of friction (μ), length-to-width ratio (l/w), and mass (m) of the part.

Results of ANOVA shown in Table 10 for aluminium indicate that the excitation frequency is the most influential factor with a contribution of 56.22 %; the second most influential factor is the coefficient of friction with 14.78 % followed by l/w ratio 13.34 % and mass 11.04 %. The least influential is the amplitude with a 4.59 % contribution, which is in line with the literature **[14]**, **[36]** and **[37]**. Increasing the amplitude of vibration might increase the conveying velocity. As seen, 80 % of the input voltage for aluminium and 90 % of the input voltage for brass are the optimal values of amplitude. However, the delta value in Fig. 16 is small for amplitude, which indicates that amplitude has a relatively small impact on the conveying velocity. Damping could be one of the reasons for the relatively small impact of amplitude. Table 11 provides the percentage contribution of each factor for brass in a similar manner.

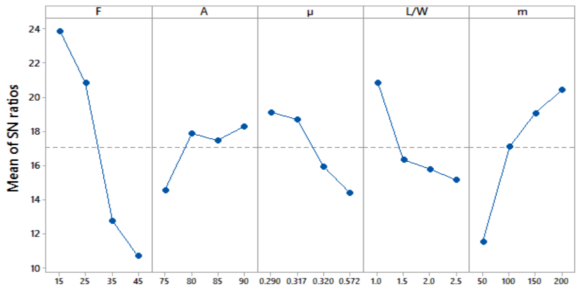

Fig. 16. *SN ratio for brass*

Table 10. *Percentage of individual factors affecting conveying velocity for aluminium*

Source	SS	% of contribution
Frequency	259.32	56.22
Amplitude	21.18	4.59
Coefficient of friction	68.31	14.78
l/w ratio	61.54	13.34
Mass	50.94	11.04
Error	395.23	
Total	461.28	

Table 11. *Percentage of individual factors affecting conveying velocity for brass*

Source	SS	% of contribution
Frequency	344.5	66.02
Amplitude	18.33	3.51
Coefficient of friction	93.47	17.91
l/w ratio	43.79	8.39
Mass	18.33	4.41
Error	426.87	
Total	521.74	

6 VALIDATION

To verify the regression model generated, a random set of experiments (combinations not included in an L16 orthogonal array) have been conducted and the parameter values of which are shown in Table 12. The comparisons of the experimental and regression results are plotted as a bar graph as in Fig. 17. The values of the regression and experimental results have been tabulated in Table 13.

Table 12. *Random experimental values for validation*

Experiment no.	f [Hz]	A [% V]	μ	l/w ratio	m [g]
1	16	76	0.331	1.5	50
2	26	81	0.331	1	100
3	36	86	0.29	2	150
4	46	91	0.29	2.5	200
5	16	74	0.419	1	50
6	26	79	0.419	1.5	200
7	36	84	0.317	2	100
8	46	89	0.317	2.5	50
9	17	87	0.629	1	200
10	27	82	0.629	2	50
11	37	87	0.572	1.5	100
12	47	92	0.572	2.5	150
13	17	73	0.445	1	150
14	27	78	0.445	1.5	150
15	37	83	0.32	2	50
16	47	88	0.32	2.5	200

From Fig. 17 and Table 13, it can be understood that the regression model results follow the same pattern as that of experimental results. The average deviation between the results of the model and experimental values was found to be 8.34 %. Hence, it could be concluded that the regression model predicted has a high correlation with the experimental results. These types of models could be used in industries to control the conveying velocity by varying the factors based on the physical characteristics of the part to be conveyed.

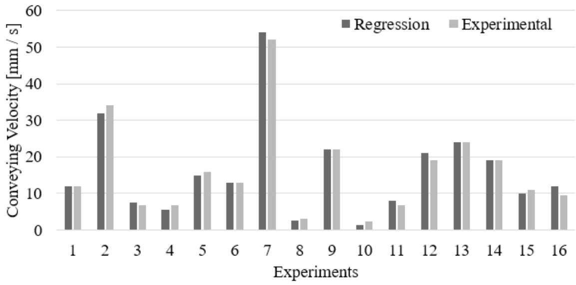

Fig 17. *Comparison of experimental and regression values*

Table 13. *Validated regression and experimental values of conveying velocity*

Experiment no.	Regression values	Experimental values
1	12	12
2	32	34
3	7.5	6.9
4	5.5	6.7
5	15	16
6	13	13
7	54	52
8	2.6	3
9	22	22
10	1.3	2.3
11	7.9	6.8
12	21	19
13	24	24
14	19	19
15	10	11
16	12	9.5

7 CONCLUSION

In this paper, an effort was made to find and understand the effect of factors such as excitation frequency (f), amplitude of vibration (A), coefficient of friction (μ), l/w ratio and mass (m) of the part on conveying velocity through experimental studies for Aluminium and brass parts.

The factors and levels were identified using the trial-and-error method. Taguchi's DOE was used to design experiments based on the five factors, each at four levels, to obtain an L16 array.

Based on the experimental results, the effects of the factors were studied and found to be highly non-linear.

Due to the complexity of developing an analytical model, a regression model was developed using Minitab software and the obtained expression for both aluminium and brass are discussed in Eqs. (1) and (2). R^2 of 99.3 % and 98.7 % for aluminium and brass, respectively, shows that the differences between the observations and the predicted values are very small. The larger R^2 value means that the regression model best fits the observations.

By using Taguchi's Design Analysis, SN ratio also has been plotted and the optimum values of each factor to maximize the conveying velocity has been determined.

ANOVA results show that frequency was the most influential parameter that affects the conveying velocity followed by the coefficient of friction and l/w ratio.

The regression model results were compared with random experimental results and the average deviation was found to be 8.34 %, which shows a high correlation between the two.

Based on the predicted model, industries can set the desired conveying velocity to maintain continuous flow of components for automated or robotic assembly.

8 FUTURE WORK

The same work can be extended to asymmetrical parts with different aspect ratios and the relationship between vibrator parameters and physical characteristics of the part can be determined.

9 NOMENCLATURES

f	excitation frequency, [Hz]
A	amplitude of vibration, % of input voltage, [% V]
μ	coefficient of friction
l/w	length-to-width ratio
m	mass, [g]
v	conveying velocity, [mm/s]

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