VIBRATION ANALYSIS OF DRILLING OPERATION

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Abstract

Vibrations are produced during any machining process. For drilling operation, analysis of these vibrations plays an important role in order to predict phenomenon of 'chatter'. This paper emphasizes the analysis of vibration during drilling operation. The output results of analysis are useful to find out amplitude of vibrations produced with respect to drill size and spindle speed for standard rate of recommended feed/min.

Analysis is quantified and tabulated as per available machining parameters of 'THAKUR PELTER DRILLING MACHINE' which is present in the Workshop of Fr. Conceiceo Rodrigues Institute of Technology, Vashi, Navi Mumbai. The optimum values of spindle speed and feed for maximium amplitude of transverse vibrations with respect to drill size are highlighted in the table and brought to the notice of Workshop Superintendent. The table of formulated results is displayed near this drilling machine.

Keywords- *Chatter, drilling operation*

I. INTRODUCTION

Drilling Process is widely used in various types of industries. During drilling many a times, a phenomenon of 'chatter' of drill bit is observed. The reason for this 'chatter' is the vibrations produced during the drilling operation. The vibrations if produced by external parameters can be controlled by the methods of vibration isolation and carrying out periodic preventive maintenance of the machine. But, vibrations produced because of drilling itself i.e. due to spindle speed and feed cannot be controlled completely.

So, such internal vibrations need to be avoided. As these vibrations depend upon the various machining parameters, calculation of vibrations can be done under different machining parameters. The results can be summarized and the critical values of machining parameters for which excessive vibration is produced can be obtained for a specific machine.

This paper deals with the mathematical analysis of the drilling operation where vibrations due to 'drilling' are solely considered and values of critical machining parameters for 'THAKUR PELTER DRILLING MACHINE' are calculated.

II. NEED OF VIBRATION ANALYSIS DURING DRILLING OPERATION

- Phenomenon of 'chatter' is widely observed during drilling operation.
- Vibration Analysis is the best solution to predict this complex phenomenon.

- Due to vibrations produced by drill dimensional accuracy of the hole gets affected. E.g. Transverse Vibration of 0.3 mm amplitude can result into enlarged hole of 0.6 mm excessive diameter.

- Vibration during drilling operation affects the surface finish of the hole produced.

- Assembly problems can be raised if the improper surface finished or enlarged holed workpiece is required to assemble with other.

- Operational Problems can be raised if such part is installed on site e.g. tube and shell heat exchanger if the size of holes on baffles is enlarged then loosening of it may happen when fluid is flowing above them.

III. SOURCES OF VIBRATION DURING DRILLING OPERATION

In Drilling Operation two types of vibrations are observed:

A. *External Vibrations*

In drilling operation spindle of drill may vibrate because of the vibration developed by machine due to malfunctioning. These vibrations can be categorized as vibrations due to external parameters. Sources of external vibrations are as follows:

- Shaft Misalignment in spindle, motor, nut-bolts and transmitting elements viz., pulley or gear drives
- Improper Foundation of machine
- Loosen fasteners such as nut-bolts, clamps etc.

B. *Internal Vibrations*

Internal Vibrations in the drilling operation are produced due to 'drilling process itself!. Internal vibrations are unavoidable as they occur because of internal characteristics of the system. Sources of Internal Vibrations are as follows:

- Spindle Speed
- Force exerted by workpiece in opposite direction to the drill motion
- Resistive torque by induced by workpiece during material cutting
- High feed rate
- High Overhung of drill

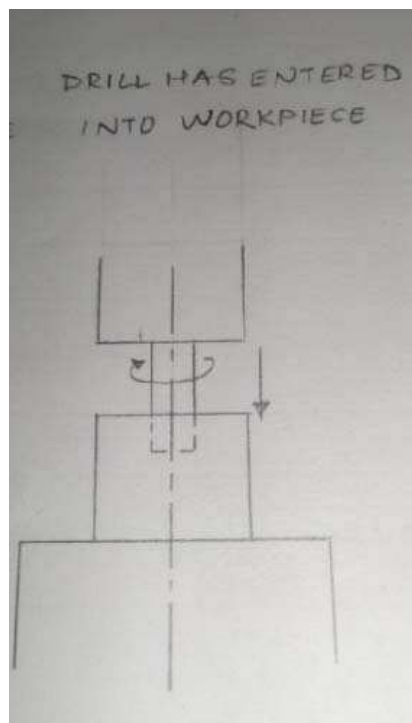### IV. TYPES OF VIBRATIONS PRODUCED DURING DRILLING OPERATION

A. *Vibrations in the drilling operation are produced in the two stages:*

1) When the drill is rotating and approaching towards workpiece
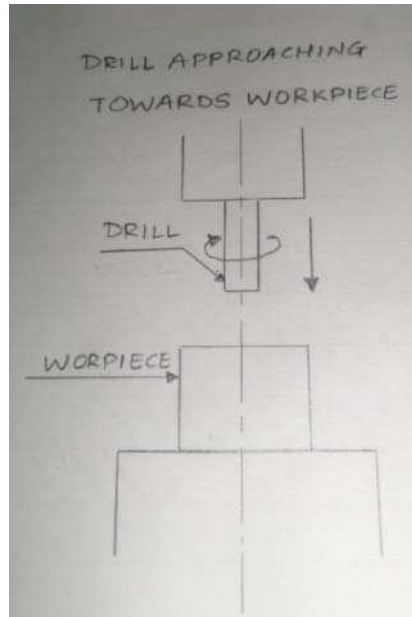
Fig 1 Drill has not entered into the work piece

2)   When the drill is rotating and drilling a hole into the workpiece

Fig 2 Drill has entered into the work piece

B. *Following types of vibrations needs to be considered for drilling operation:*

1)   **Free Vibration:** Free vibration of the system helps to determine natural frequency of the system (ω_n).

2) **Forced Vibration:** Forced vibrations are produced because of rotation of spindle. These vibrations have frequency of external excitation (ω) which is nothing but spindle speed in rad/sec. In forced vibration we have to consider force applied by the machine on the tool in no loading (Stage 1) and resistive force applied by the workpiece during drilling operation (Stage 2).

V.   THEORY PART (MATHEMATICAL ANALYSIS)

A. Assumptions

1) Only the vibrations produced because of machining are considered. Effect of external vibrations is neglected as these vibrations can be controlled with various techniques. On the other hand internal vibrations which we are analysing can be controlled only by adopting safe machining parameters.

2) During analysing of particular type of vibration, only that type is assumed to be taking place. Effect of the other types is neglected for that analysis

3) We have considered cylindrical drill bit for the analysis as our scope is to find out the vibrations that are going to take place not the cutting operation which is being carried out.

4) During our analysis our main focus is concentrated on the transverse vibrations. This is because of the fact that the transverse vibrations produced during drilling operation are the main cause of the enlargement of the diameter of hole being produced beyond tolerance limit.

B. Actual Procedure

1) For the drilling operation following three types are observed:

- Transverse Vibrations
- Longitudinal Vibrations
- Torsional Vibrations
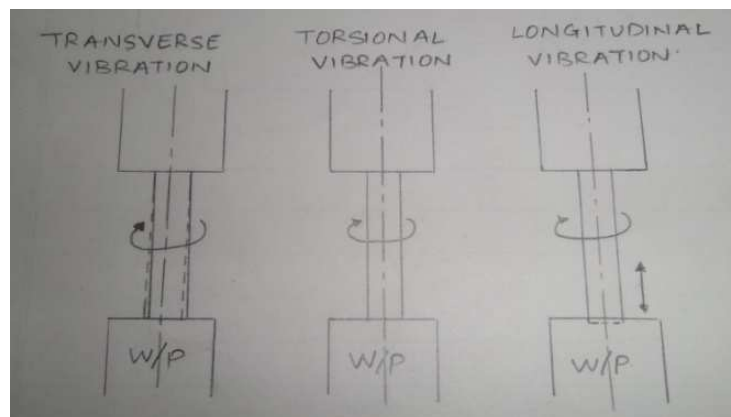
Fig 3 Types of vibrations

2) Following procedure essential for Vibration Analysis of the drilling operation:

   o   Identification of the type of vibrations produced during machining operation

   o   Determination of the factors affecting these vibrations

   o   Applying concepts of the equilibrium to solve the problem

   o   Finding out the forces that are exerted on the tool under various conditions

LIST OF SYMBOLS:

d = Diameter of drill

l = Length of drill

E = Young's Modulus

σ = Tensile Strength

τ = Shear strength

ω = Frequency of vibration

ω_n= Natural Frequency

ω_t = Frequency with which spindle is rotating

V = Tangential velocity of drill

r = Radius of drill

F = Force

ξ = Damping ratio

A = Amplitude of excitation

B = Amplitude of support

- **Longitudinal Vibrations**

1) Free Longitudinal Vibration Analysis:

Free longitudinal vibrations exist in the drill which are produced due to self-weight of the drill. These vibrations can be analysed with the help of the following formula:

$$\omega_n = \sqrt{\frac{k_{retaing\ spring}}{m}}\ \text{rad/sec}$$

$$\omega_n = \frac{1}{2\pi}\sqrt{\frac{k_{retaining\ spring}}{m}}\ \text{Hz}$$

However these vibrations are not useful when we want to analyse the 'chatter' phenomenon of the drilling operation.

Hence these vibrations are not considered during preparation of our table.

2) Forced Longitudinal Vibrations Analysis:

  Cases:

   1) When the drill is rotating and approaching towards work piece

   Forced Longitudinal Vibrations do not exist when drill is approaching towards the work piece. It is because of the fact that as drill is approaching, no force acts on the drill in the upward direction.

Due to this, the vibrations of the drilling during approaching towards the workpiece can be neglected.

2) When the drill is rotating and drilling a hole into the work piece.

When drill touches the work piece and starts cutting the material to produce the hole, the upward resistive force acts on the drill because of the tensile stress of the work piece material.

When the material breaks during drilling the hole, its failure in the longitudinal direction can be considered as the compressive failure.

The force exerted in the upward longitudinal direction during the failure of the workpiece can be calculated using the following formula:

$$F = \sigma_{workpiece} * \frac{\pi}{4} * d^2$$

The amplitude of the forced longitudinal vibration can be computed using the formula given below[5]:

$$\therefore \frac{A}{B} = \frac{\sqrt{1 + \left(2\xi\frac{\omega}{\omega_n}\right)^2}}{\sqrt{\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\xi\frac{\omega}{\omega_n}\right)^2}}$$

For our drilling machine we have considered no damping condition (since we want to consider the worst possible case)

i.e. $\xi = 0$

$$\therefore \frac{A}{B} = \frac{1}{1 - (\omega/\omega_n)^2}$$

However, these longitudinal vibrations can be restricted with the help of restricting spring or suitable damping mechanism. These vibrations however, do not effect on the diameter of the hole produced.

In Thakur Pelter Drilling Machine, which is used for very simple applications, these vibrations can be neglected since this machine is generally practiced to produce through holes only.

- **Torsional Vibrations**

1) Free Torsional Vibration Analysis:

Free torsional vibrations exist in the drill which can be computed as follow:

$$\omega_n = \sqrt{\frac{k_t}{I}} \text{ rad/sec}$$

but,

$$k_t = \frac{GJ}{l}$$

$$I=mk^2=\frac{md^2}{8}$$

$$\omega_n=\sqrt{\frac{GJ}{l}*\frac{8}{md^2}}$$

$$m=\rho*\text{volume of drill}$$

$$\therefore m=\rho*\frac{\pi}{4}d^2*l$$

$$\therefore \omega_n=\sqrt{\frac{GJ}{l^2}}$$

$$\therefore \omega_n=\frac{1}{l}\sqrt{\frac{G}{}}\;\text{rad/sec}$$

These vibrations are useful to determine torsional natural frequency of the system (ω_{nt})

This frequency is useful to obtain the forced natural torsional frequency of the system.

2)   Forced Torsional Vibration Analysis:

Cases:

1)   When the drill is rotating and approaching towards work piece.

No resistive force exerts on the drill in torsional direction when drill is approaching towards the work piece and hence the vibrations produced can be neglected.

2)   When the drill is rotating and drilling a hole into the work piece.

When drill enters into the work piece and starts cutting the material, torsional shear failure of the material takes place.

   Force exerted on the drill material during torsional failure of the work piece material can be computed as below:

$$F=\frac{\pi}{16}*d^3*\tau_{Workpiece}$$

Where,

$$F=\frac{T}{d/2}$$

Torque exerted is related with power in the following manner:

$$P=\frac{2\pi NT}{60}$$

Torsional Vibrations are created because of the rotary motion of drill. These vibrations create resistive twisting moment on the drill and higher values of these vibrations may break the drill.

Formula for finding amplitude of forced torsional vibration (θ) is given as:

Considering value of damping to be negligible,

$$\frac{\theta}{\alpha_o} = \frac{k_t}{k_t - P}$$

However as these vibrations do not affect in the transverse direction of motion which is responsible for the enlargement of the hole. Thus it is not considered in the calculation.

- **Transverse Vibrations**
  1) **Free Transverse Vibrations Analysis:**
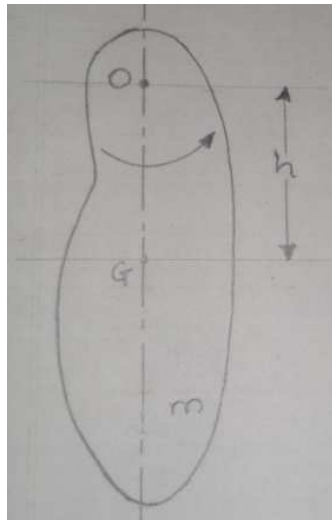
Fig 4 Free transverse vibrations in any body[2]

The Vibrations in the drill in free state i.e. w/o rotation can be assumed as free transverse vibrations (as in case of compound pendulum)

The Natural Frequency of the free transverse vibration (ω_n) can be computed by using following formula:

$$\omega n = \sqrt{\frac{mgh}{I}}$$

But, mass moment of inertia,

$$I = \frac{ml^2}{2} + \frac{ml^2}{4}$$

$$\therefore \omega n = \sqrt{\frac{g * \left(\frac{l}{2}\right)}{\frac{l^2}{2} + \frac{l^2}{4}}}$$

$$\therefore \omega_n = \frac{3.835}{\sqrt{1}}$$

2) Forced Transverse Vibration Analysis

Cases:

1) When the drill is rotating and approaching towards work piece

When the drill approaches towards the work piece, the no external force on the drill except the force of vibration developed by the motor torque.

And thus these vibrations can be neglected because there is no restricting force acting on the drill bit in the direction of the transverse vibration of the drill.

2) When the drill is rotating and drilling a hole into the work piece.

When drill enters into the workpiece, the force is exerted by the workpiece material on the drill bit in the direction of the transverse motion of the drill. i.e. perpendicular to the axis of the drill.

The analysis of this force can be understood from the following diagram:
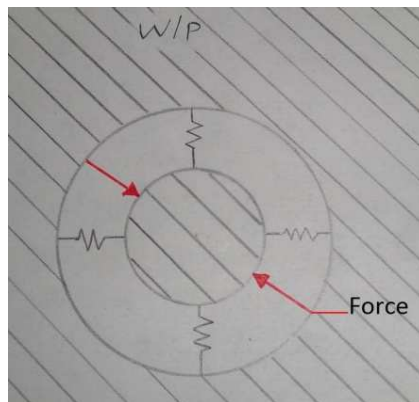
Fig 5 Force analysis during transverse vibration

The drill and work piece are considered to be attached with the help of the spring whose stiffness is 'k'.

Under equilibrium conditions,

$$k = \sigma * v$$

This is because of the fact when the drill transverses with the linear velocity 'v', the force is exerted on the drill in the direction of the transverse motion due to the stress induced in the material.
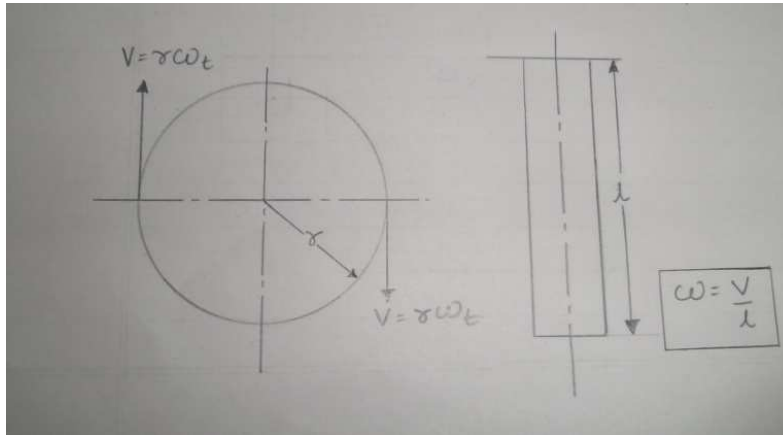
Force is the resistive force applied by the work piece in the direction perpendicular to the axis of the drill.

$$F = \sigma_{Workpiece} * \frac{\pi}{4} d^2 * (feed/sec)$$

The forced frequency of transverse vibration can be computed with the help of following procedure:

N= rpm of the spindle

$$\omega_t = \frac{2\pi N}{60};$$

Fig 6 Free transverse vibrations in any body

The relation between angular velocity and linear velocity of the drill cross section in the transverse direction can be given in the following manner:

$$v = \frac{\omega_t * d}{2}$$

Now consider, the length of the drill oscillating at forced transverse frequency of 'ω' in the following manner:

$$\omega = \frac{v}{l}$$

Now the amplitude of the transverse forced vibration when the drill enters into the workpiece can be computed by using the following formula[3]:

$$A = \frac{\frac{F}{k}}{\sqrt{\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\xi \frac{\omega}{\omega_n}\right)^2}}$$

For our drilling machine we have considered no damping condition (since we want to consider the worst possible case)

i.e. $\xi = 0$

$$\therefore A = \frac{1}{1 - (\omega/\omega_n)^2}$$

IV. PRACTICAL APPROACH

SAMPLE CALCULATIONS (For N=92 rpm, feed = 4.6736 mm/min, drill diameter =3.175mm

DATA:

d=0.00317m

l=0.150m

E=4.461*10^{9}N/m^2

$\sigma = 420 * 10^6 \text{N/m}^2$ [4]

TO FIND OUT:

$$\omega, \omega_n, K, F, A$$

SOLUTION:

For 92 rpm

$\omega_t = 2 * \Pi * N / 60$

$= 2 * \Pi * 92 / 60$

$= 9.63 \text{rad/sec.}$

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Spindle speed (rpm)	Feed (mm/min)	Drill size (mm)	Maximum Amplitude Of Vibration (mm)
92	2.3368-4.6736	<3.175	0.051
	7.0104-14.0208	3.175-6.35	0.155
	9.3472-23.368	6.35-12.7	0.258
	16.3576-35.052	12.7-25.4	0.38
165	4.191-8.382	<3.175	0.051
	12.573-25.146	3.175-6.35	0.15
	16.764-41.91	6.35-12.7	0.256
	29.337-62.865	12.7-25.4	0.38
285	7.239-14.478	<3.175	0.053
	21.717-43.434	3.175-6.35	0.15
	28.956-72.39	6.35-12.7	0.25
	50.673-108.585	12.7-25.4	0.38
504	12.8016-25.6032	<3.175	0.051
	38.4048-76.8096	3.175-6.35	0.15
	51.2064-128.016	6.35-12.7	0.26
	89.6112-192.024	12.7-25.4	0.43

TOLERANCE:=±0.3mm

Fig 7 Chart prepared for the workshop

$\omega_n = 3.835/\sqrt{l}$

$\quad = 3.835/\sqrt{0.150}$

$\quad = 9.901 \text{rad/sec.}$

$F = \Pi * d * (\text{feed/sec}) * \sigma$

$\text{Feed/sec} = ((\text{feed/rev}) * N)/60$ [1]

$\quad\quad = (0.0508 * 0.001 * 92)/60$

$\quad\quad = 7.789e^{-5} \text{m/sec}$

$F = \Pi * 0.00317 * 7.789e^{-5} * 420e^{6}$

$\quad = 329.84 \text{N/sec}$

$v = \omega_t * r$

$\quad = 9.63 * 0.00317/2$

$\quad = 0.015 \text{m/s}$

$K = \sigma * v$

$\quad = 420e^{6} * 0.015$

$\quad = 63e^{5} \text{N/m}$

$\omega = v/l$

$\quad = 0.015/0.150$

$\quad = 0.1 \text{rad/sec}$

$\omega/\omega_n = 0.1/9.901$

$\quad\quad = 0.01$

$A = (F/K)/(1-(\omega/\omega_n)^2)$

$\quad = (329.84/63e^{5})/(1-0.01^2)$

$\quad = 0.051 \text{mm}$

A=0.051 mm

Fig 8 Photograph with Workshop Superintendent near the Thakur Pelter Drilling Machine along with the chart displayed

V.   CONCLUSIONS

We used the straight and simplified approach in the analysis of the vibrations produced during drilling operation on "THAKUR PELTER DRILLING MAHCINE". We arrived to the conclusion that the "chatter" phenomenon is produced due to the transverse vibrations of the drill, which adversely affect the assembly problem. Longitudinal vibration only changes the length of blunt hole and does not affect the though hole. Torsional vibration leads to the removal of the material from the workpiece with the help of chisel edge and flanks on drill, but does not affect the dimensions of the hole. This report is the best example to show that how the theory knowledge gained in the academic curriculum can be effectively applied to the practical scenario.

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