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Investigation of chatter arising in machine tool-fixture work (MTFW) system during turning

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Experimental investigations have been conducted to determine the influence of the rigidity of tool holder, cutting variables and tool geometry on machine tool chatter during turning of different grades of carbon steel with cemented carbide tools. Experimental results show that these variables maintain definite relationship with the frequency, amplitude and cutting speed range of high frequency chatter. A mathematical model has been developed to calculate the frequencies of the natural vibration of the tool holders. Finally it was concluded that high frequency chatter of machine tools during turning can be controlled by selecting the appropriate values of the rigidity of the tool holder, proper combination of cutting speed, feed and depth of cut and geometry of the tool.

1. INTRODUCTION

Machine tool chatter is a type of intensive self-excited vibration of individual components of the Machine-Tool-Fixture-Work (MTFW) system. Chatter leads to shorter machine tool life, intensive tool wear, poor surface finish of the work piece, lower output and fatigue of the operator due to sharp whistling sound caused by chatter. Chatter appears during metal cutting as a result of resonance caused due to the interaction of the instability of chip-formation process and self vibration of the spindle-work system or the tool holder.

It has been established by Talantov N.V. and his co-researchers that the chip-formation process of titanium alloys, heat resistant and stainless steel at all cutting speeds and that of carbon steel at high cutting speeds is unstable (1), (2). This type of instability leads to the formation of "cyclic chip". This type of chip is similar to segment chip on external view. Its formative cycle consists of two phases - the phase of compression and the phase of shear. Frequency of formation of chip elements increases with cutting speed. It has been established that when the frequency of instability of chip formation is close to the natural frequency of the spindle-work system resonant vibration of the latter is observed. During resonance the spindle-work system vibrates with almost a constant frequency which is close to the frequency of natural vibration of the spindle-work system. Amplitude of vibration increases with cutting speed and attains a maximum value inside the cutting speed range of resonance vibration (4).

Similarly when the frequency of the instability of chip formation is close to the natural frequency of the tool holder, resonance is again observed and the tool holder vibrates with an almost constant frequency within a wide range of cutting speed. The amplitude of vibration again attains a maximum value at a point inside the cutting speed range (4). It has been observed that work materials cutting parameters and rigidity of the spindle-work system mainly influence the frequency and amplitude of chatter and the location and extent of the cutting speed range of low frequency chatter. On the other hand the frequency, amplitude and cutting speed range of high frequency chatter is a function of mainly of the work material, cutting parameters tool geometry and rigidity of the tool holder.

It may be noted here that the resonant vibration of the spindle-work system occurs at relatively low cutting speeds which are rarely employed in production for metal cutting with cemented carbide tools. Keeping in view the above mentioned the present work aimed at investigations of high frequency chatter (of the tool holders). A survey of literature on the remedies of chatter revealed the following:

When chatter is observed within a cutting speed range generally the cutting speed is recommended to be lowered to ensure chatter free machining. But this leads to lowering down of productivity. In another method visco-elastic and other types of dampers are employed to damp vibration. But the prestrains of these dampers have to be adjusted at different locations of the carriage, which present an inconvenience in the use of such dampers.

In the light of the above mentioned the aims and objectives of the present work were set as mentioned below:

1.1 Aims and Objectives

The following were the aims and objectives of the present work:

1. To develop a mathematical model for calculating the frequency of natural vibration of the elastic system of the tool holder.
2. To determine by experimental method the frequencies of natural vibration of the tool holders to validate the theoretically determined values.
3. To determine the influence of the rigidity/frequency of natural vibration of the tool holder on the frequency and amplitude of chatter and also on the chatter accompanying cutting speed ranges.
4. To determine the influence of feed, depth of cut and tool geometry on the characteristics of chatter.

2.0 DETERMINATION OF THE FREQUENCIES OF NATURAL VIBRATION OF THE TOOL HOLDERS

2.1 Mathematical Model for determining the frequency of natural vibration

During chatter the amplitude of cutting force versus the time curve takes the following shape:

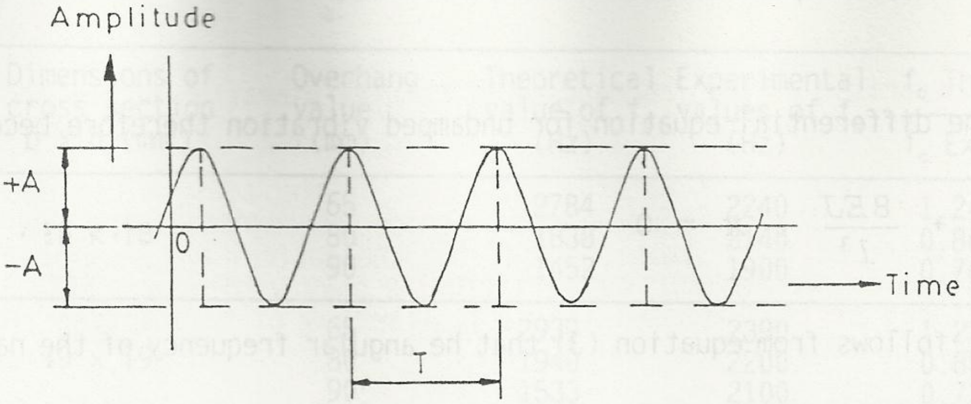

Fig.1 : Amplitude of cutting force vs.Cutting time curve during chatter

The shape of the above mentioned curve indicates that during chatter the damping is zero (3). In the case of turning operation the weight of the tool holder may be assumed to be distributed uniformly along the length of the tool holder. Deflection of the tool holder under its self weight may be represented by the following diagram.

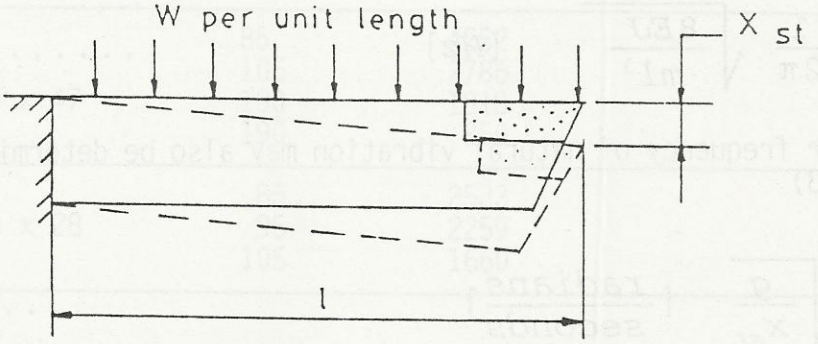

Fig.2 :Diagram of bending of the tool holder due to self weight

The deflection may be calculated using equation-1

$$x_{st} = \frac{wl^4}{8EJ} \qquad \ldots\ldots \quad (1)$$

where

x_{st} = deflection of the tool holder

w = weight per unit length of the tool holder

l = overhang of the tool holder

E = modulus of elasticity of the tool holder. for steel E = 2000 Ton/cm^2

J = area moment of inertia of the tool holder

The spring constant C is obtained by dividing the weight by the deflection caused. i.e.

$$C = \frac{8EJ}{l^3} \qquad \ldots\ldots \quad (2)$$

The differential equation for undamped vibration therefore becomes

$$m\ddot{x} + \frac{8EJ}{l^3} \cdot x = 0 \quad \ldots\ldots \quad (3)$$

It follows from equation (3) that he angular frequency of the natural vibration is

$$w_o = \sqrt{\frac{8EJ}{ml^3}} \quad \left[\frac{radians}{seconds}\right] \quad \ldots\ldots \quad (4)$$

The natural frequency may be expressed as follows :

$$f_o = \frac{1}{2\pi} \sqrt{\frac{8EJ}{ml^3}} \quad [Hz] \quad \ldots\ldots \quad (5)$$

Angular frequency of natural vibration may also be determined by the following equation(3)

$$w_o = \sqrt{\frac{g}{x_{st}}} \quad \left[\frac{radians}{seconds}\right] \quad \ldots\ldots \quad (6)$$

Correspondingly the natural frequency of vibration may be determined by the following equation:

$$f_o = \frac{1}{2\pi} \sqrt{\frac{g}{x_{st}}} \approx \sqrt{\frac{25}{x_{st}}} \quad [Hz] \quad \ldots\ldots \quad (7)$$

Substituting the values of x_{st} from equation (1) into equation (7) and after simplification the following equation is obtained:

$$f_o \simeq 6.5 \times 10^4 \; \frac{H}{l^2} \quad \ldots\ldots \quad (8)$$

It may be observed from equation (8) that the frequency of natural vibration is independent of the width of the tool holder. It is directly proportional to the height of the tool cross section and inversely proportional to the square of the tool holder overhang, measured from the last fixing bolt(towards the workpiece).

A computer program was written in BASIC to compute the values of the natural frequencies of all the tool holders corresponding to their different overhang values. These values are given in Table-1.

Table -1. Dimensions of the tool holder and their natural frequencies

Tool Holder	Dimensions of cross section b x h (mm^2)	Overhang value (mm)	Theoretical value of f_o (Hz)	Experimental values of f_o (Hz)	$\frac{f_o \text{ Theo}}{f_o \text{ Expt}}$
T-1	18 x 18	65	2784	2240	1.24
		80	1838	2140	0.86
		90	1452	1900	0.76
T-2	19 x 19	65	2939	2390	1.23
		80	1940	2200	0.88
		90	1533	2100	0.73
T-3	20 x 20	65	3093	2800	1.10
		80	2042	2560	0.80
		90	1613	2160	0.75
T-4	18 x 28	80	2859		
		95	2027	-	
		110	1512		
T-5	20 x 47	85	4252		
		105	2786	-	
		130	1818		
		190	850	-	
T-6	20 x 28	85	2533	-	-
		95	2259	-	-
		105	1660	-	-

2.2 Determination of the Frequencies of Natural Vibration of the Tool Holders by experimental Method:

Frequency of Natural Vibration of three tool holders were determined by experimental methods to judge the validity of the theoretically determined values. The experimental setup used for this purpose is shown in block diagram of Fig.3. In this method forced vibrations of different frequencies were supplied from the function generator, through the amplifier and the vibrator head to the cutting tool to excite its resonance. The vibration signal of the tool was picked up by a specially designed pressure transducer, amplified by a charge amplifier and displayed onto an oscilloscope screen. The oscilloscope signals were visually analyzed and also photographed for further data processing. From these data the frequencies of natural vibration of the tool holders corresponding to their different overhang values were determined. In this method initially the different resonant frequencies were recorded. Natural frequencies of the tool holders were determined after careful analysis and elimination of the repeating natural frequencies of the components of the experimental setup, such as the body of the vibrator head, its holding stand, etc. Values of the natural frequencies of the tool holder, determined by this method are shown in *Table - 1*

2.3 Comparison of the frequencies of natural vibration of the tool holders determined by the theoretical and experimental methods.

The frequencies of natural vibration of the tool holder determined by the experimental method were compared with those determined by the theoretical method. It was observed from Table-1 that the theoretical and experimental values are very close to each other. The variation is only within +/- 25%. This proves the correctness of the proposed theoretical method of calculating the frequency of natural vibration of the tool holder.

3.0 Determination of the influence of the natural frequencies of the tool holders and cutting parameters on chatter.

3.1 Methodology

Cutting tests were conducted at room temperature employing natural dry turning. Experimental setup used for these investigations is shown in Fig.4. As it may the observed from the figure that. vibration signals were picked up from the tool holder by a transducer. This signal was amplified at the charge amplifier and fed onto the oscilloscope screen. These signals were visually observed and also photographed for data processing. Occurrence of instability (chatter) was indicated by sudden increase in the vibration amplitude. Frequencies of the instability , f_c of the chip formation from the reading of the oscilloscope using the following formula:

$$f_c = \frac{n}{t.m} \; [Hz] \qquad \ldots\ldots \qquad (9)$$

where,
t = sweep time, sec/cm.
n = number of observed waves
m = length of n waves, cm.

Chatter Frequency, f_c was also calculated from the wave length L,mm of the chatter mark on job surface and known cutting speed. V, m/sec. using the following relationship:

$$f_c = \frac{V}{100 \times L} \; [Hz] \qquad \ldots \qquad (10)$$

The values of f_c determined by these two methods were compared to eliminate any error of reading of the electrical equipments.

3.2 Experimental Results

3.2.1 Influence of Rigidity (natural frequencies) of Tool Holders on Chatter

Cutting parameters for these investigations were set as fillows. Depth of cut t = 1.5. 2.0 mm and feed s = 0.20, 0.467 mm/rot. The results of these experiments are shown in Fig.5 a,b,c and Fig.6. From Fig.5a it was observed that for tool holder of cross section of 18 x 18 mm^2 and overhangs values 65.80 & 90 mm chatter appeared at cutting speeds 1.90,1.55 and 1.40 m/sec. respectively. The chatter

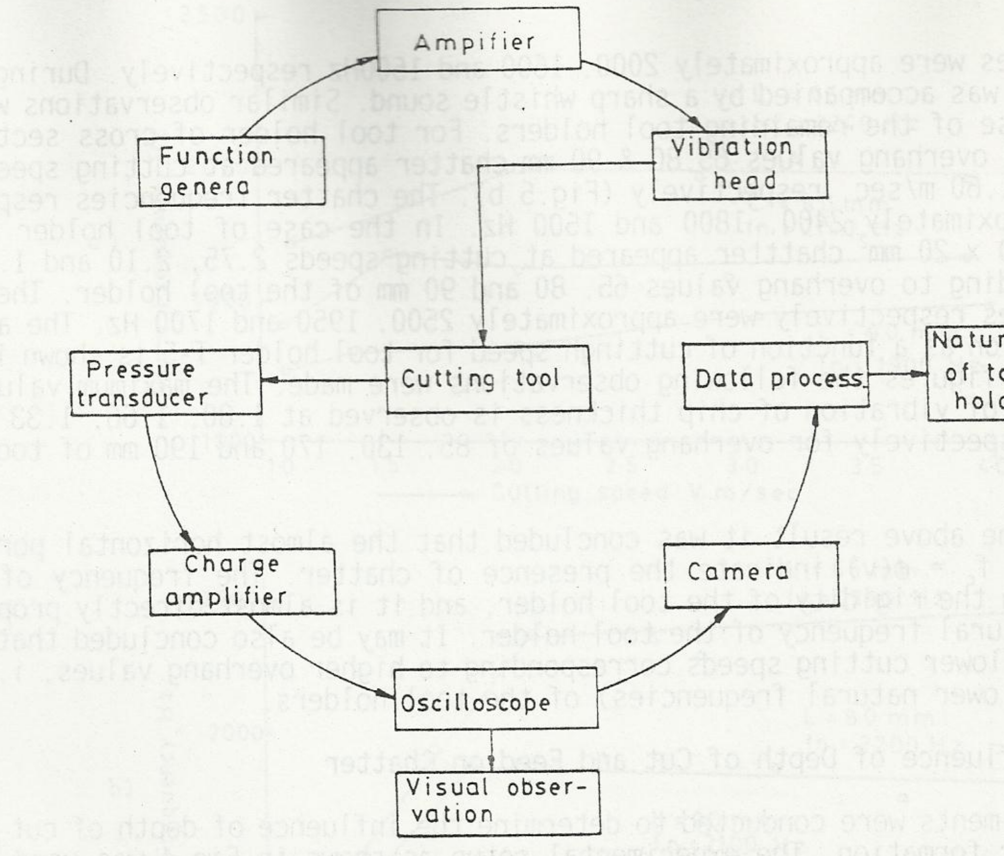

Fig.3 Block diagram of the experimental setup for natural frequency determination

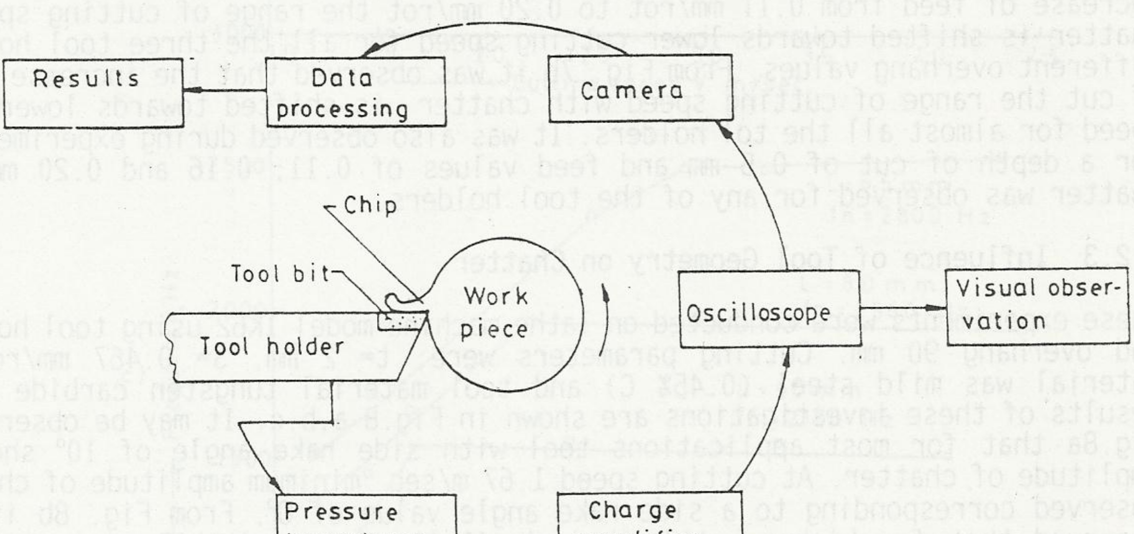

Fig. 4 Block diagram of the experimental setup for determining the influence of the tool holder and cutting variables on chatter

frequencies were approximately 2000, 1600 and 1500Hz respectively. During chatter machining was accompanied by a sharp whistle sound. Similar observations were made in the case of the remaining tool holders. For tool holder of cross section 19 x 19 mm^2 and overhang values 65,80 & 90 mm chatter appeared at cutting speeds 2.15, 1.90 and 1.60 m/sec. respectively (Fig.5 b). The chatter frequencies respectively were approximately 2400, 1800 and 1500 Hz. In the case of tool holder of cross section 20 x 20 mm^2 chattter appeared at cutting speeds 2.75, 2.10 and 1.60 m/sec corresponding to overhang values 65, 80 and 90 mm of the tool holder. The chatter frequencies respectively were approximately 2500, 1950 and 1700 Hz. The amplitude of vibration as a function of cuttingh speed for tool holder T-5 is shown in Fig.6. From this figures the following observations were made. The maximum value of the amplitude of vibration of chip thickness is observed at 1.80, 1.66, 1.33 and 1.00 m/sec. respectively for overhang values of 85, 130, 170 and 190 mm of tool holder T-5.

From the above result it was concluded that the almost horizontal portions of the curve $f_c = \phi(v)$ indicate the presence of chatter. The frequency of chatter depends on the rigidity of the tool holder, and it is almost directly proportional to the natural frequency of the tool holder. It may be also concluded that chatter begins at lower cutting speeds corresponding to higher overhang values, i.e. lower rigidity(lower natural frequencies) of the tool holders.

3.2.2 Influence of Depth of Cut and Feed on Chatter

Experiments were conducted to determine the influence of depth of cut and feed on chatter formation. The experimental setup as shown in Fig.4 was used for this purpose. Tool holders T-1, T-2, T-3 were used in the experiments. Various combinations of feed and depth of cut values were taken for this investigation. The results are shown in Fig. 7 a, b. As it was observed from Fig. 7a that with the increase of feed from 0.11 mm/rot to 0.20 mm/rot the range of cutting speed with chatter is shifted towards lower cutting speed for all the three tool holders of different overhang values. From Fig. 7b it was observed that the increase of depth of cut the range of cutting speed with chatter is shifted towards lower cutting speed for almost all the tol holders. It was also observed during experiments that for a depth of cut of 0.5 mm and feed values of 0.11, 0.16 and 0.20 mm/rot no chatter was observed for any of the tool holders.

3.2.3 Influence of Tool Geometry on Chatter

These experiments were conducted on lathe machine model 1K62 using tool holder T-6 and overhang 90 mm. Cutting parameters were: t= 2 mm, S= 0.467 mm/rot. Work material was mild steel (0.45% C) and tool material tungsten carbide BK-8. Results of these investigations are shown in Fig.8 a,b,c. It may be observed from Fig.8a that for most applications tool with side rake angle of 10° show lower amplitude of chatter. At cutting speed 1.67 m/sec minimum amplitude of chatter is observed corresponding to a side rake angle value of 0°. From Fig. 8b it may be observed that for higher cutting speeds (1.41 m/sec and 1.67 m/sec.) the side clearance angle of 5° is found to be optimum from the point of view of vibration stability. From Fig.8c it may be observed that the side cutting edge angles of 45° and 65° corresponds to lower amplitude values of chatter.

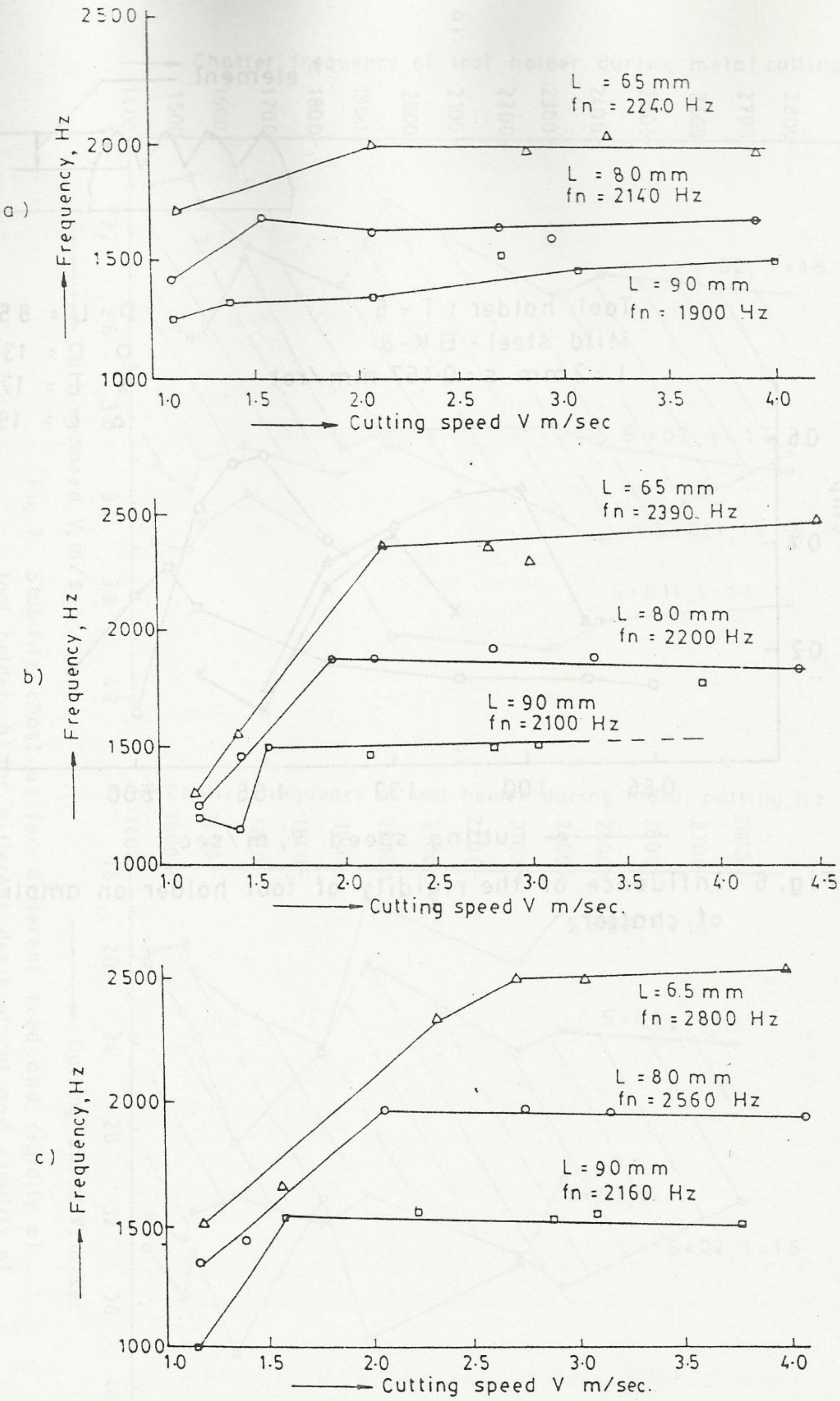

Fig. 5 Influence of rigidity of tool bit holder on the frequency of chatter Tool holder cross section a) 18 x 18 mm b) 19 x 19 mm c) 20 x 20 mm

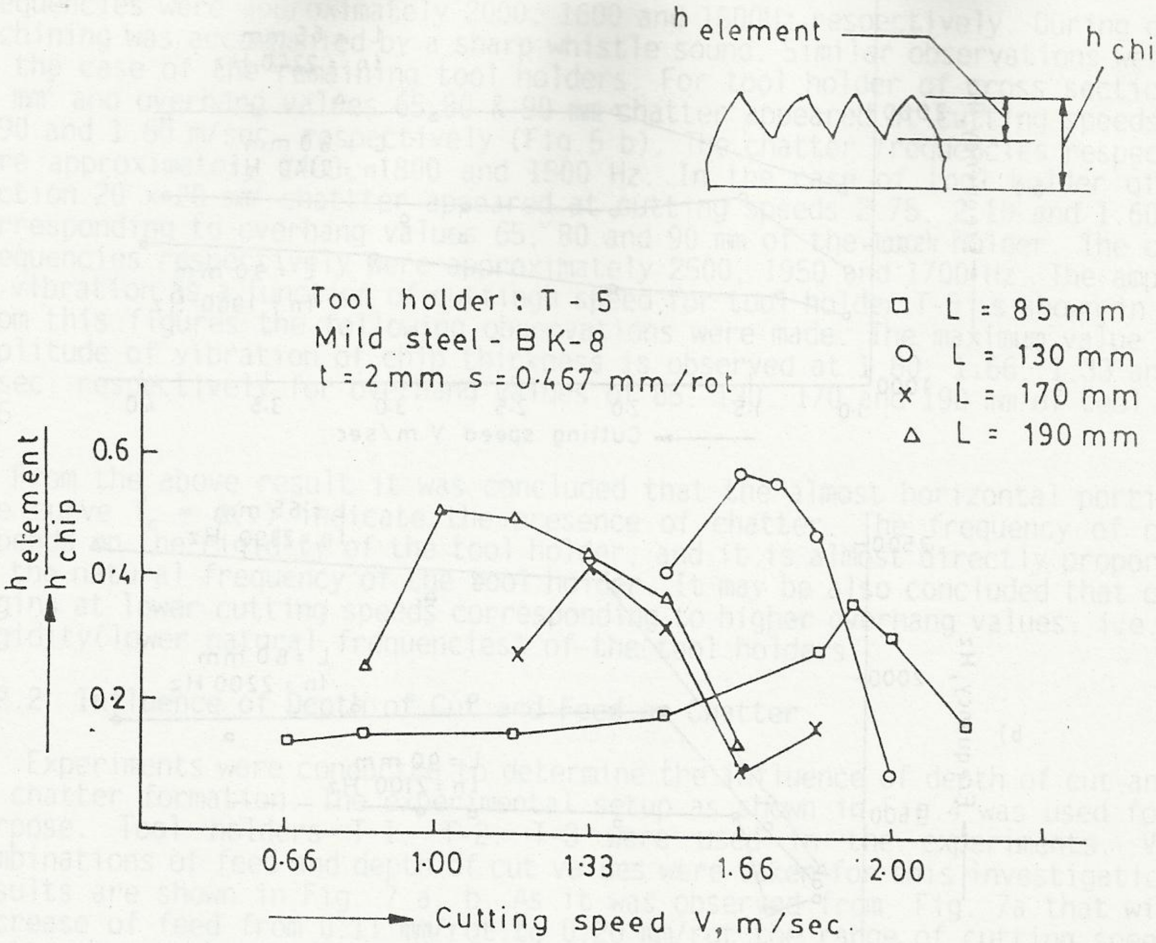

Fig. 6 Influence of the rigidity of tool holder on amplitude of chatter.

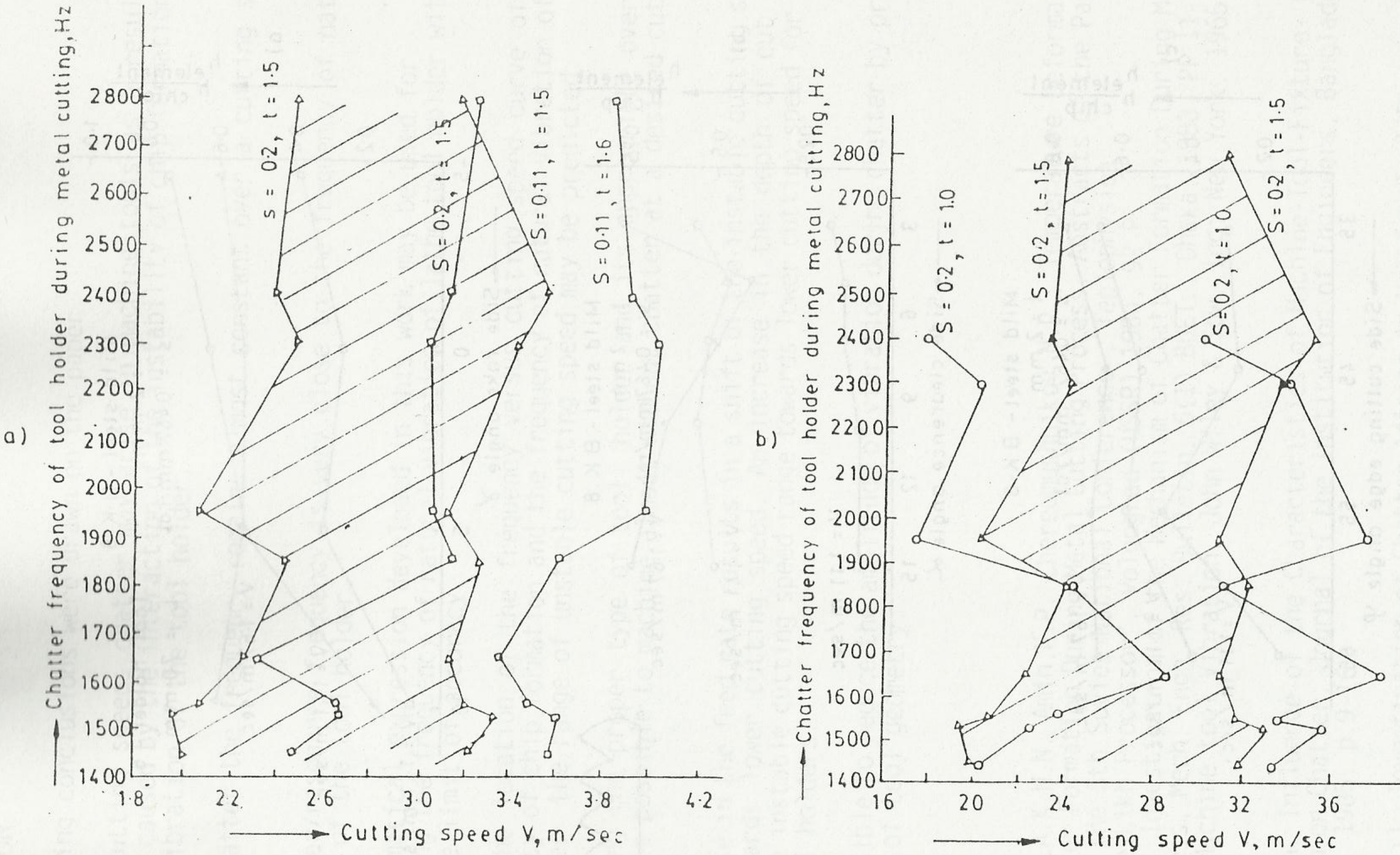

Fig. 7 Stability chart a) for different feed and rigidity of tool holder b) for different depth of cut and rigidity of tool holder

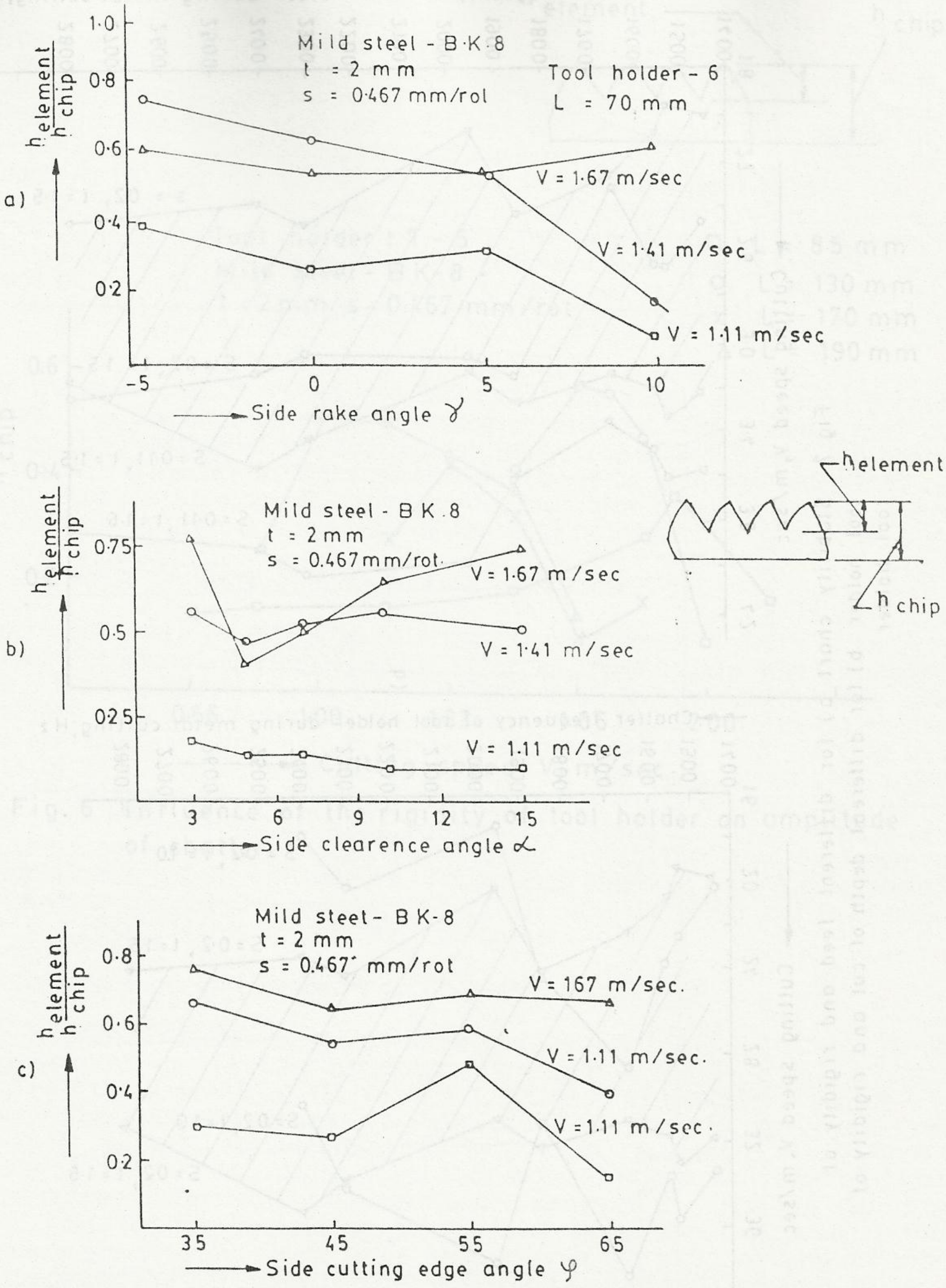

Fig. 8 Influence of tool geometry on amplitude of chatter
a) Side rake angle γ b) Side clearence angle α
c) Side cutting edge angle φ

4.0 CONCLUSION

The following conclusions were drawn on the paper.

1 At high cutting speeds chatter may arise in machine tools as a result of resonance caused by the interaction of the instability of chip formation and natural vibration of the tool holder.

2 During chatter the frequency remains almost constant over a cutting speed range.

3 The chatter/resonance frequency is very close to the frequency of natural vibration of the tool holder.

4 The mathematical expression developed in this work may be used for calculating the frequency of natural vibration of lathe tool holder with an acceptable limit of accuracy.

5 Knowing the location of the frequency versus cutting speed curve of the instability of chip formation and the frequency of natural vibration of the tool holder the range of unstable cutting speed may be predicted.

6 By choosing the proper type of tool holder and its appropriate overhang value it is possible to machine almost without chatter at a desired cutting speed.

7 An increase in the feed rate results in a shift of the instable cutting speed range towards lower cutting speed. An increase in the depth of cut also shifts the instable cutting speed range towards lower cutting speed for less rigid tool holders.

8 It is possible to reduce the amplitude of vibration during chatter by proper selection of tool geometry.

REFERENCE

1. N.V.Talantov,A.K.M.N. Amin,N.P. Chereomushnikov N.P., Temperature Deformation Laws of Chatter Formation During Metal Cutting Process. Abstracts of the Papers presented at the 5th Soviet National Conference :"Teplophysica Technoligicheskikh Processov", Volgograd (USSR) 1980, 92 P.
2. A.K.M.N.Amin, Investigation of the Mechanism of Chatter Formation During Metal Cutting Process, Mech. Engg. Res. Bulletin, 6(1) BUET., Dhaka, 1983, PP 11-18.
3. S.A.Tobias, Machine tool Vibration, John Wiley & Sow, Inc; New York, 1965, P P 350.

4. A.K.M.N. Amin, Influence of the Characteristics of Machine-Tool-Fixture- Work (MTFW) system on Chatter, Journal of the Institution of Engineers, Bangladesh, 13(4), Dhaka, 1985, p.9-16.

5. M.Khaled Khalil, Investigation of Chatter Arising in Machine-Tool-Fixture-Work (MTFW) system During Metal Cutting Process, M.Engg. (IP) Project, IPE Dept., BUET, Dhaka, 1989.