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THE SUPPRESSION OF VIBRATION IN MACHINING

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Abstract

Metal cutting operations are prone to vibration with a consequential reduction in surface finish quality and the generation of excessive noise. This is particularly true of the unstable vibration commonly called chatter. Various models of the vibration in machining have been developed, however, the number that have led to practical solutions is limited. This paper describes some animation programs that have been written to give students and production engineers a good understanding of chatter. Also the simplest analysis of chatter, that is realistic and allows practical solutions, is presented. With these two aids it is then possible to discuss methods of vibration suppression and how they work. As chatter is an instability it is not just a question of reducing the vibration amplitude by a desired percentage, it is possible to eliminate chatter if the machining process can be made stable.

INTRODUCTION

Vibration in machining processes is usually regarded as either no problem at all or a major limitation. Thus vibration and its elimination is often of little interest until it becomes the major obstacle in achieving a required finish or is causing prohibitive tool wear or may even be endangering the operator because of noise or the possibility of the workpiece being released. It follows that the machine tool builder must aim to design chatter free machines and production engineers know how to eliminate chatter.

The correct identification of the type and source of any vibration problem is the first and the major step toward its solution. Vibration problems that occur in machining processes may conveniently be divided into two major groups for which the methods of solution are different and sometimes conflicting. The first group may be given the general heading of "forced vibration problems". These result from a periodic excitation which does not increase in amplitude with time. The second group may be given the general heading of "instability problems" which are normally called "chatter problems". These are made distinctive by a vibration which is not present immediately machining starts but which builds up with time at a rate depending on the process. The limit to the amplitudes attained is determined by either tool failure, workpiece shifting or a non-linear limiting amplitude being attained. In the latter case machining may become intermittent at the frequency of vibration.

This paper is directed at methods of suppressing chatter however it must be stressed that forced vibration is often called chatter though the methods to be applied for its reduction are different. The approach to be adopted in this paper is to develop the theory of chatter as necessary to allow the understanding of some good inventions for the suppression of chatter.

REGENERATIVE FORCE

Regenerative chatter arises when a small oscillation of a cutting edge results in a wave being left on the surface. The following tooth, or the same tooth one revolution later, has to remove this wave and, depending on the width of cut, leaves a wave of smaller or greater amplitude. When the latter is the case each succeeding tooth leaves a wave of greater amplitude, resulting in a vibration of large amplitude. The situation shown in figure 1 represents the conditions existing at the boundary of stability when each tooth leaves a wave of the same amplitude.

As a first approach to the suppression of chatter various means of reducing the regenerative force will be considered. These methods involve modification of multi-tooth cutters. Clearly if the regenerative force were reduced to zero then regenerative chatter would not be possible. Consider the regenerative force caused by a conventional cutter; it is necessary to consider the removal of a surface wave left by a preceding tooth. Figure 2 shows such a wave being removed. Note the effect on the force of the vibration of the tooth in cut is neglected at this stage. The variation of the cross sectional area of the chip as the tooth removes a complete wave may be determined by considering the tooth in the positions numbered 1 to 9. In the position shown in full—ie position 1—the chip cross-section is shown shaded and is the mean chip cross-section. The chip cross-sections at the positions 1 to 9 are also shown in figure 2 where the area over or under the mean is shown shaded. This is the important parameter since it is only oscillating forces that are of interest and not the mean steady forces. The maximum variation of the chip area from the mean has been defined as 100 units and the variation of the area from the mean with tooth position is also shown in figure 2. If the force is proportional to the cross-section area an oscillating force of amplitude proportional to 100 acts on the tooth.

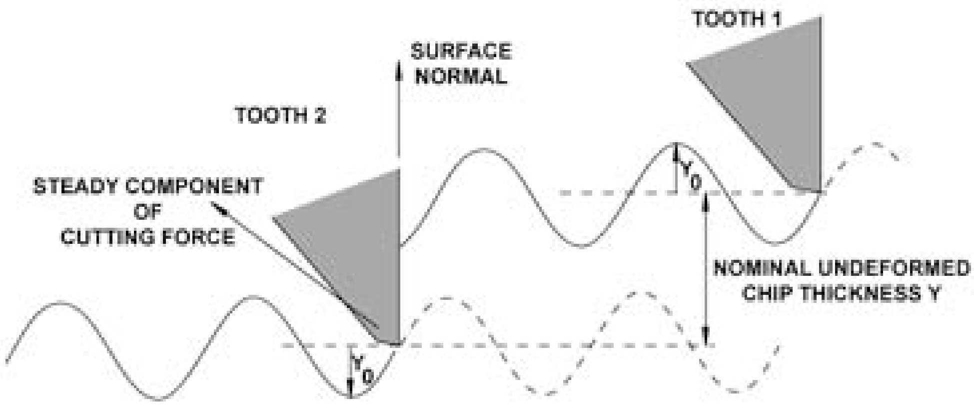


Figure 1 Simplified boundary of stability

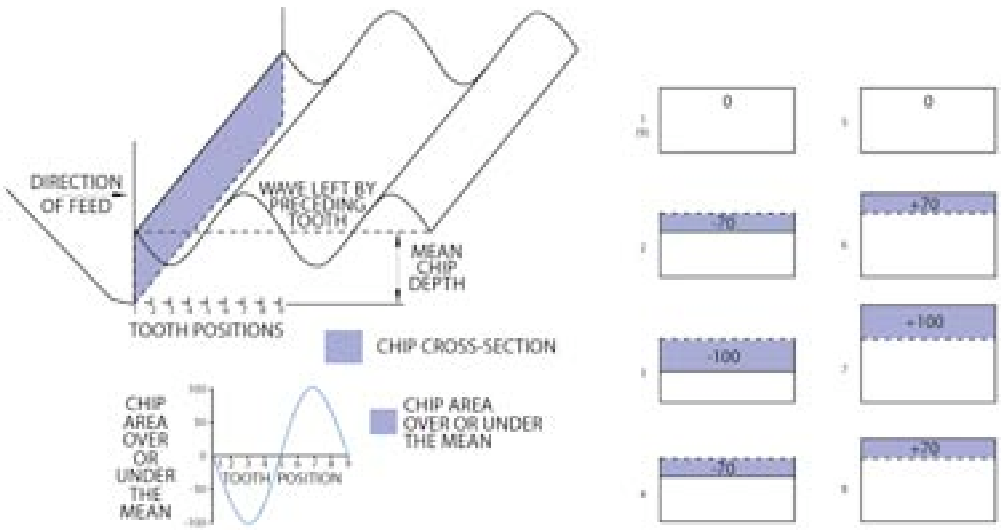


Figure 2 Removal of a surface wave

In 1969 Stone [1] suggested that the use of alternating helix (or bi-helix) cutters could substantially reduce the regenerative force and hence suppress chatter. For comparison with the constant helix case the removal of a wave of the same amplitude will be considered and the units of area will be the same. The difference in helix angle results in the waves left by the preceding tooth being at an angle to the tooth in cut. Thus the tooth in cut will cross the waves left by the preceding tooth and may span more than one wave. As an example a difference in helix resulting in the tooth in cut crossing one and two-thirds waves is considered. This condition is shown in figure 3 with the chip cross-section shaded for the tooth position 1.

The variation of the chip cross-section as the tooth moves through positions 1 to 9 may be determined and these chip cross-sections are also shown in figure 3 with the area over or under the mean shown shaded. It may be seen that at each position considered the areas above and below the mean line are nearly equal and that the net area above or below the mean is greatly reduced compared with the constant helix case. The amplitude of the oscillating area is now 16.5 compared with the 100 for the constant helix cutter.

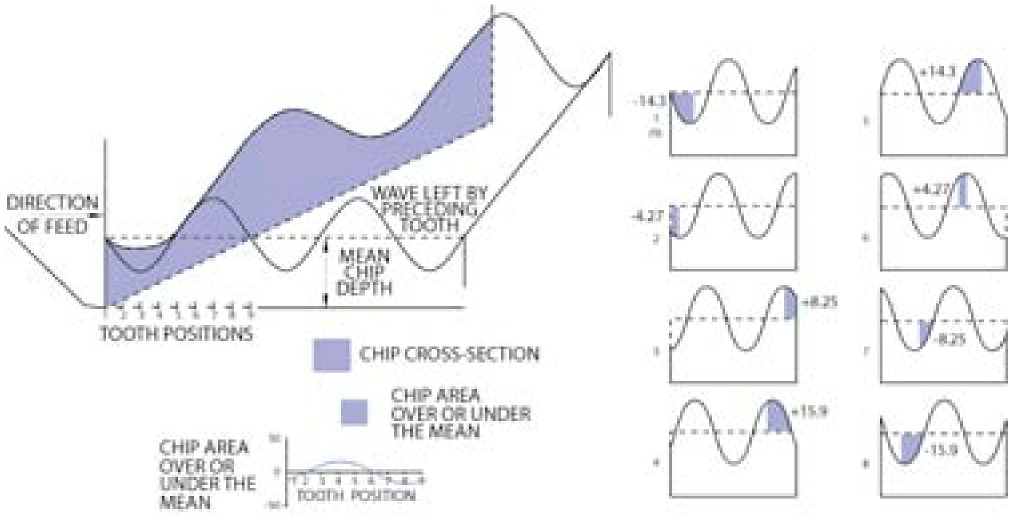


Figure 4 Removal of surface wave by a tooth at a different helix angle

The example considered applies only to a particular helix difference resulting in one and two-thirds waves being crossed. However, for different wavelengths, which arise at different cutting speeds and vibration frequencies, and also for greater or smaller differences in helix angle, the number of waves crossed will vary. The reduction in the regenerative force amplitude also varies. An animation program [2] allows the two helix angles to be varied and the effect on the regenerative force observed. Experimental results obtained with such cutters indicate an improvement by up to a factor of four [1] in the width of cut that may be taken without chatter. Other chatter resistant cutters may be examined in the same way [3] and their effect on the regenerative force assessed. For machining with multi-tooth cutter a suitable chatter resistant tool will often be the solution to the problem.

SIMPLE CHATTER THEORY

It is also possible to improve chatter performance by modifying the structural response. In order to appreciate how this is effected it is necessary to develop a simple model of chatter. For this analysis we will consider the situation at the boundary of stability as shown in figure 1. If the machine was vibrating sinsusoidally then it will continue to do so with no increase or decrease in the amplitude of vibration. The oscillation of the tool and the regenerating wave on the surface will cause an oscillating force which acts on the structure to maintain the cutting tool oscillation. For a constant amplitude oscillation let

$$x(t) = X_o \sin(\omega t + \phi) \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

The oscillating force on a single tooth is given by,

$$F = -Rb\left[x(t) - x(t-\tau)\right] \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where R is the cutting force coefficient and b the width of cut. The force is thus assumed to be proportional to the undeformed chip cross section. Thus substituting from (1) in equation (2), gives the oscillating force as,

$$F = -Rb\left[X_o \sin(\omega t - \phi) - X_o \sin(\omega(t-\tau) - \phi)\right] \quad \ldots\ldots\ldots \quad (3)$$

We may now draw the two parts of this force on the response locus of the machine tool, see figure 6. The response shown is for a single degree of freedom system for simplicity but a complex response may be treated in the same way. The response locus has the rotating force vector located along the positive real axis. The displacement vector is then at an angle ϕ to this.

If we now consider the two components of the force, the non-regenerative force F_n and the regenerative force F_r are located as shown in figures 5 and 6, where from equation 3,

$$F_n = -RbX_o \sin(\omega t - \phi) \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$
$$F_r = RbX_o \sin(\omega(t-\tau) - \phi) \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

If these force components are now drawn on the response locus we obtain the diagram shown in figure 5. The chatter frequency is ω_c and the various vectors are in the directions shown. This may be more easily understood by observing an animation of the vibration and rotating vectors [4] Note that the magnitude of both the force components is RbX_o so that from simple geometry the force has a magnitude $2RbX_o\cos(180-\alpha)$. For the situation shown in figure 5 let OC = S represent the response amplitude. Thus

$$S = \frac{X_o}{F} = \frac{X_o}{2RbX_o\cos(180-\alpha)}$$

so that rearranging we obtain

$$b = b_{lim} = \frac{1}{2RS\cos(180-\alpha)}$$

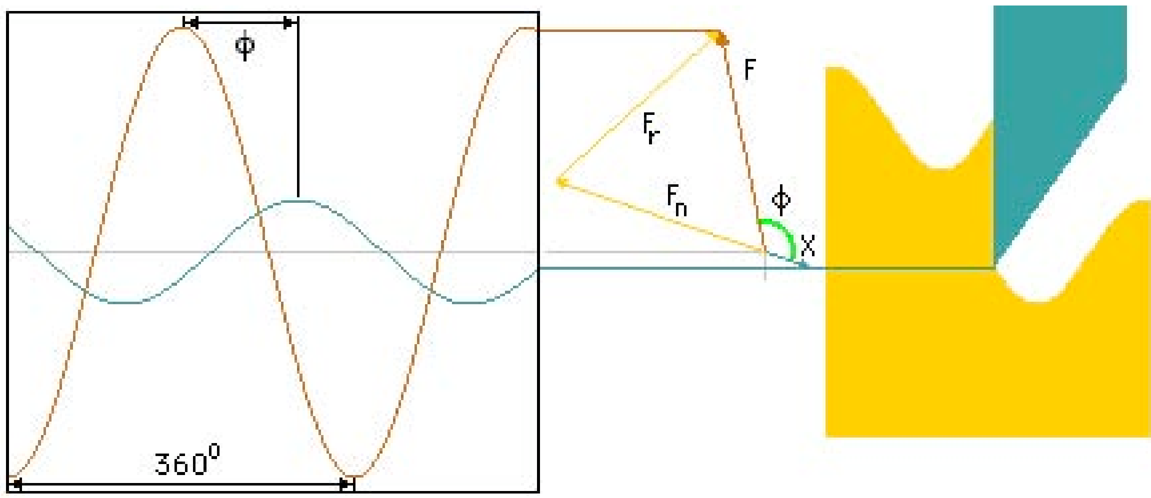


Figure 5 Cutting force components.

This value of the width of cut (b) is normally called the limiting width b_{lim} as at this width vibration does not increase or decrease in amplitude. If the force acts in space at some angle β to the direction of vibration then the exciting force component in the direction of vibration is,

$$2RbX_0\cos(180-\alpha)\cos\beta$$

and the equation for b_{lim} becomes

$$b = b_{lim} = \frac{1}{2RS\cos(180-\alpha)\cos\beta} \quad .. \quad (6)$$

Note that in figure 5,

$$GC = S\cos(180-\alpha).$$

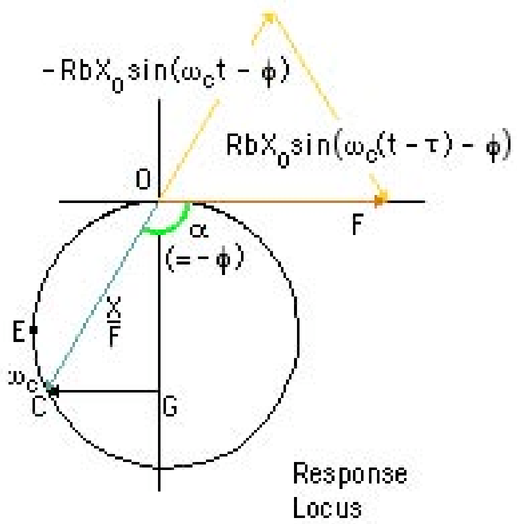
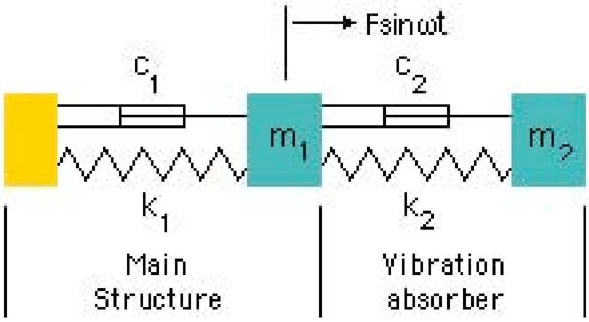


Figure 6 Response locus with force vectors.

This is the negative inphase component of the response at C. It follows that the smallest value of b_{lim} is when the chatter frequency is at E, which is called the maximum negative inphase component of the response. It is the objective in making structural modifications to the machine tool to minimise the maximum negative inphase component of the response.

VIBRATION ABSORBERS

The theory of vibration absorbers is well known. However such absorbers are normally optimised with a view to minimising the maximum response. For optimising chatter performance a different optimum is required. To illustrate this consider a simple one degree of freedom system to which a vibration absorber is added.



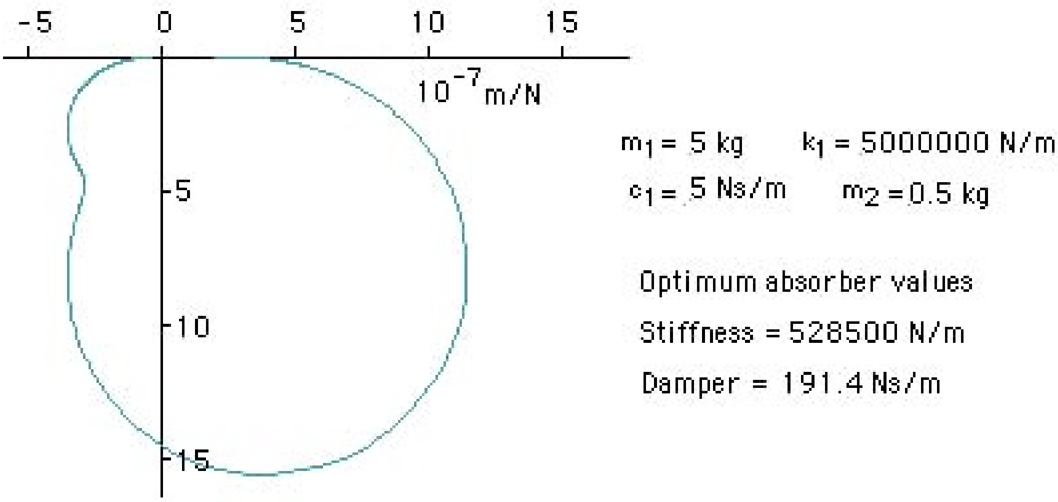
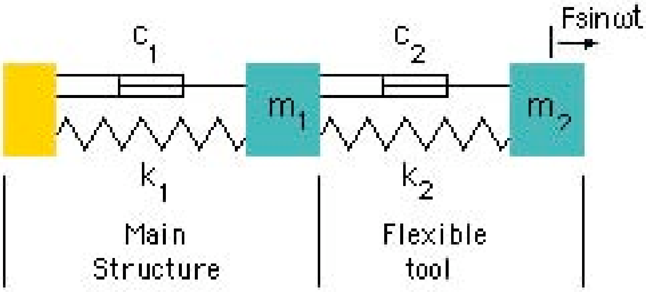


Figure 7 Optimised absorber for chatter performance

The optimised response curve is shown in figure 7. Vibration absorbers have been used with great success in machining set ups that initially had low damping [5].

FLEXIBLE TOOLS

It has been found that the use of a flexible tool may also be used to improve chatter performance. The model of such tooling is shown. An additional spring/mass/damper system is interposed between the cutting point and the machine.



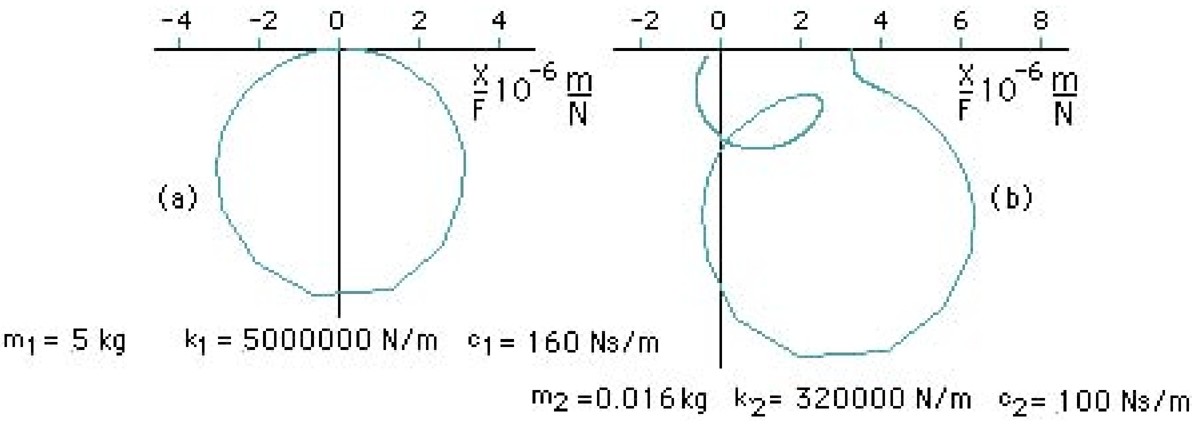


Figure 8 a) original response b) with flexible tool

Figure 8 shows an example of what may be achieved. Such flexible tools have been made for turning and grinding [5] with significant improvements in chatter performance.

CONCLUSIONS

The simple chatter theory developed in this paper allows for solutions to chatter problems to be found. It has been found in practice [1, 3, 5, 6] that these solutions are effective in the real situation. It follows that any assumptions made in developing the theoretical modes do not restrict the solution of chatter problems by the means suggested. Further it is hoped that the animations developed to aid with the understanding of the methods described will be useful to both students and practitioners alike.

REFERENCES

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