Non Linear Static and Dynamic Analysis of End Milling Cutter with Multiple Fingers

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Abstract: Milling is the process of removing unwanted material with suitable tool. Even though the milling process is having wider application, the vibration of machine tool and work piece during the process produces chatter on the products. Various methods of preventing the chatter have been incorporated into machine tool systems. Damper is cut into equal number of parts. Each part is called as finger. Multiple fingers were inserted in the hollow portion of the shank to reduce tool vibrations. In the present work, non linear static and dynamic analysis of the damper inserted end milling cutter used to reduce the chatter was done. A comparison is made for the milling cutter with multiple dampers .In all the cases, milling cutter is modeled .Linear and non linear analysis is done to find the effect of number of fingers in the damper of the end milling cutter. In addition, non linear dynamic analysis is also performed.

Keywords: End milling, vibrations, Damping inserts, Number of fingers, Non linear dynamic analysis.

1. Introduction:

Conventionally, milling has been regarded as a slow and costly process. The main limitation of milling is caused by the vibration of the machine tool and work piece. As the speed and the power of milling are increased, it is very important to control vibration of the tool. If vibration is not controlled, it will have adverse effect on the performance of the machine tool.The material removal rate is also limited by chatter vibration. Cutting operation in milling is affected by two different kinds of vibration, Self excited vibration at high spindle speed and Vibration at critical natural frequency. In this paper, non linear static and dynamic analysis of the damper inserted end milling cutter has been done.

2. Literature Review:

Several efforts were made to reduce the chatter on the products produced by the milling process. Sridhar et al (1968) presented the first detailed mathematical model with time varying cutting force coefficients. Zhu et al(1982) developed a fuzzy logic control to control the surface finish by adjusting the feed rate in plunge grinding. Ralston and Ward (1988) proposed the use of spindle speed modulation by adjusting the parameters on-line via feedback control. Owing to the availability of a suitable analytical model and the inherent non linearity of the chatter phenomenon in milling process, it was found that the fuzzy logic control approach was well suited for the current investigation.

Engelhardt et al (1989) have been demonstrated the technique of spindle speed modulation to be very effective in suppressing chatter in milling at regular cutting speeds.The speed modulation parameters are application specific and may not be suitable for entire job. The static force variation that results from modulated feed per tooth could produce undesirable effects where constant speed cutting may suffice. Hence this technique on its own lacks broad applicability.

Delio et al (1992) have described a control strategy for chatter suppression by adjusting the spindle speed to operate in high stability lobe. Experimentally, they achieved a remarkable increase in metal removal rates. The main disadvantage of employing this spindle speed selection method however, is that meaningful stability lobes occur at very high speeds, beyond most of the available milling machines in industry.

Tlusty and Smith (1992) suggested the use of stability lobes to select chatter free spindle speeds. Once chatter has been detected in their system, the feed was stopped while the chatter vibrations were analyzed. A new spindle speed was then calculated and invoked, and the feed was reinstated. While the results reported in the above work were impressive, they did not offer true online strategies for chatter suppression. They require the stopping the machines, which may need several commands depending on the part of the geometry and other path. In addition meaning stability lobes occur at very high speeds which necessitates highly specialized drives.

Weck et al (1994) attempted to assess the merits of using the spindle speed modulation and for that matter any other technique for chatter suppression, one needs to detect the onset chatter reliably. This blurring is amplified drastically when applying certain chatter suppression techniques like spindle speed modulation method. The limit of stability is defined as the axial depth of cut at which chatter commences.

J.Tlusty et al (1996) showd two techniques using end mills in high-speed milling to reduce the chatter. In the first method, the top speed and power of the spindle are accepted as fixed, and the structural dynamics are manipulated by adjusting the tool length so as to take the advantage of stability lobe effects. The second technique permits the machining of parts with very thin ribs.

F. Ismail and E.G. Kubica(1996) proposed the maximum quantity of material that can be removed by the milling operation is often limited by the stability of the cutting process, and not by the power available on the machine.Proportional Derivative fuzzy logic controller is designed and implemented by E. Soliman and F. Ismail (1997) to suppress chatter in peripheral milling. The controller was successful in suppressing the chatter at certain operating points. The effect of the control action delay time and the degree of process instability on the controller performance was addressed through simulations and experiments. Strategies for enhancing the performance of the controller were proposed.

Budak and Altintas (1998) derived the finite order characteristic equation for the stability analysis in milling. N.H.Kim et al (2000) proposed a continuum-based shape design sensitivity formulation for a frictional contact problem with a rigid body using mesh less method. Kosuke Nagaya et al (2002) gave a method of micro-vibration control of milling machine heads by use of vibration absorber. An auto-tuning vibration absorber is presented in which the absorber creates anti-resonance state. A method of optimal auto-tuning control is presented in which both principal and higher modal vibrations are suppressed.

M. Liang et al (2004) reported a fuzzy logic approach for chatter suppression in end milling processes. Vibration energy and the peak value of vibration frequency spectrum are jointly used as chatter indicators and inputs to the proposed fuzzy controller. The outputs of the fuzzy controller are the altered machining parameters for chatter suppression. This approach does not require a pre-selected nominal spindle speed and has avoided the difficulties in selecting spindle speeds modulation parameters present in several other spindle speed variation methods. Experimental results show that chatter can be effectively suppressed by altering spindle speed alone or by simultaneously adjusting feed and spindle speed. However chatter cannot be suppressed by feed adjustment alone.

T. Schmitz et al (2004) predicted that the stable cutting regions are a critical requirement for high-speed milling operations. J.C.Ziegert et al (2004) found that the limiting chatter-free depth of cut in milling is dependent on dynamic stiffness of the tool or spindle system. A method for increasing the dynamic stiffness by providing additional damping is demonstrated. The proposed damper is multi-fingered cylindrical insert placed in an interior bore located inside conventional milling cutters. Spindle rotation forces these flexible fingers against the inner surface of the tool, bending of the tool during cutting dissipate energy through friction, leading to improved damping and dynamic stiffness. This presents an analytical model of the damper, experimental measurements of tool response and comparison between stable cutting depths using both conventional tool and with the damping insert.

G.Krishna mohana Rao and P.Ravi kumar (2011) conducted experiments on end milling in aluminium and mild steel using solid end milling cutters .It was observed that surface roughness decreases as the cutting speed increases. G.Krishna mohana Rao and P.Ravi kumar (2012) conducted experiments on damper inserted end milling cutters . Influence of cutting speed and type of damping insert on the roughness of surface produced by damper inserted end mill cutter was studied.Taguchi method was applied and found that hollow end milling cutter with 2 dampers was optimum.

From above study it is evident that the change in the design of end miller will reduce the chatter vibrations. In present work ,non linear static and dynamic analysis was done for multi fingered end mill cutter by ANSYS. This will enable to design optimum mechanical damper.

3. Methodology:

The tool considered is a 4" long end mill, as shown in Fig.3.1. Most end mills are of the solid beam type. In this type of tool, the only available damping mechanism is structural damping, which is very small. Structural damping, which is a variant of viscous damping, is usually caused by internal material friction. When the damping coefficient is small, damping is primarily effective at frequencies close to the resonant frequency of the structure.

When a layered-beam damper is inserted into the hollow tool, the high-speed rotation causes a strong contact between the beam and tool. When chatter vibration occurs, it generates a relative motion between the beam and tool. Due to the contact force, this relative motion causes a friction force in the interface, which damps the vibration. In this work, the damping mechanism will be referred to as a mechanical damper. While the tool geometry is very important for cutting performance, the objective of this work is mainly based on the vibration of the tool. Here simplified tool geometry is selected so that the analytical and numerical studies in the following chapters will be convenient. The first step of simplifying the end mill model is to suppress unnecessary geometric details, while maintaining the end mill's mechanical properties. The end mill model can be simplified as a cylinder because we are only interested in the contact surface, which is the inner surface of the tool. Fig 3.2 illustrates the simplified model.

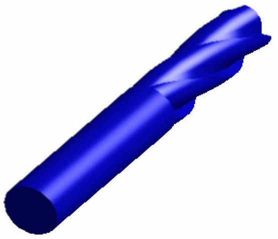


Fig. 3.1 Solid beam with flutes

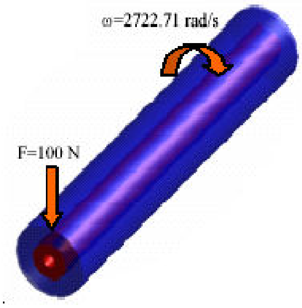


Fig. 3.2 Simplified model with load and angular velocity

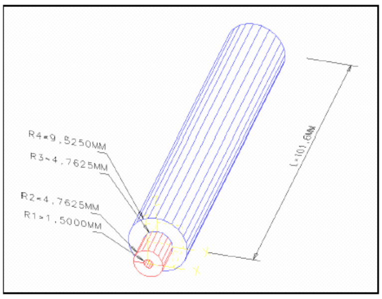


Fig. 3.3 Dimensions of tool geometry for end mill with single damper design

The simplified end mill model is composed of two-hollowed cylinders. The outer cylinder represents the end mill tool, and the inner cylinder represents the damper. For convenience, the outer part (tool) is denoted as a shank, while the inner part (damper) is denoted as a finger. As schematically illustrated in Fig.3.3, the outer radius R_1 of the finger is 1.5 mm, the inner radius R_2 of the finger is 4.7625 mm, the inner radius R_3 of the shank is 4.7625 mm, and the outer radius R_4 of the shank is 9.525 mm. The length of the end mill is 101.6mm. Because the gap between two contact surfaces is ignored, R_2 is equal to R_3. R_1 is taken as 1.5mm.

Although Fig.3.3 shows only one finger, the number of fingers can be altered to improve the damping performance. Because a damper with only one finger would have a lower contact pressure than the other cases, this case is not considered. The applied force is assumed to be sequential. It is first assumed that the tool is rotated with a constant angular velocity. The constant angular velocity will generate a constant contact force at the interface. For this particular model, an angular velocity of 2,722.713rad/sec is used, which is equal to 26,000 r.p.m. In this initial state the end mill has not started cutting the surface. When the end mill starts cutting the surface, the tool experiences a vertical force at the end of the end mill. To approximate the cutting process of the tool, a vertical force is applied at the tip. To the cutting force, the vertical force on the end mill needs to be measured and then an equal force needs be applied at the tip. However, since the objective of this work is vibration control, an assumed representative force of 100 N is applied. Thus, the damping work that will be calculated is not the actual magnitude, but rather a relative quantity.

For simplicity, the same material properties are assumed for both the shank and finger even though the stiffness of the finger is actually slightly higher than that of the shank. The material properties used are listed in Table 3.1.

Table 3.1 Material properties of High speed steel

Material Property	Value
Young's Modulus	206780MPa
Mass Density	7.82×10^{-9}ton/mm^3
Friction Coefficient	0.15

4. NON LINEAR STATIC ANALYSIS

The analysis of end mill is carried out using ANSYS R10. The geometric model of the end mill is carried out as a hollow cylinder and damper is inserted as a hollow circular rod. The internal radius of end mill is equal to the external radius of the dampers.

A 20 noded brick element solid95 from ansys library is used to mesh the end mill and the damper. A surface to surface contact (contact 174 and target 170 from ansys library) between the damper and end mill is enforced. The converged meshed model is shown in figure4.1. A load of 100N is applied at the tip of the end mill. The angular velocity is assumed to be 2722.713rad/sec.

The No. of brick elements : 1008,
The No. of contact elements : 120,
The No. of target elements: 120.

5. Results and Discussions:

5.1.TWO FINGER DAMPER

Damper is cut into two equal halves each part of which is called as finger. This is the case of 2 finger dampers, so the fingers are in contact with each other. Angle made by each finger is 180 degrees. Fig. 5.1 shows the variation of resultant displacement. The maximum value of resultant displacement is 0.514E-3mm at the tip of the end mill where the end mill touches the work piece. It has it's minimum value at the fixed end because there is no displacement at that point.

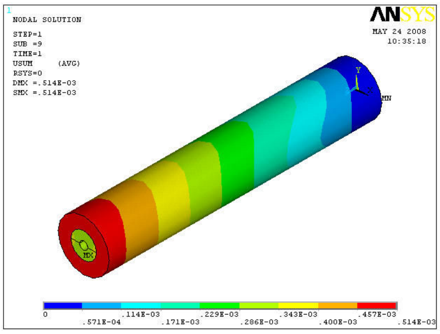


Fig. 5.1. Resultant displacement for 2 finger damper with no load

Fig. 5.2 shows the variation of von mises stress. The maximum value of von mises stress is 7.006MPa and is developed where there is maximum contact. The value of von mises stress is less even for the non contact part of the end mill but has it's least value for the non contact part of the damper. Fig. 5.3 shows the variation of contact pressure. The maximum value of it is 0.589308MPa and the minimum value is on the outer surface of the end mill and the inner surface of the damper. To understand the performance of the end mill cutter under loaded conditions , a load of 100 N is applied at the point where the tip of the tool touches the work piece while keeping the angular velocity at 2722.713 rad/sec.

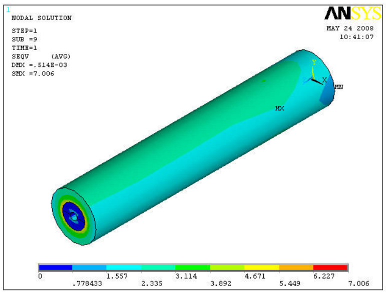


Fig.5.2. Von misses stresses for 2 finger damper with no load

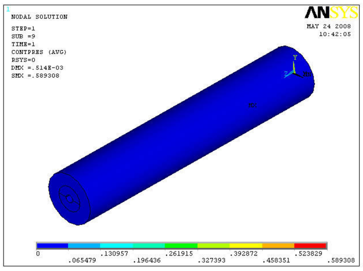


Fig.5.3.Contact pressure for 2 finger damper with no load

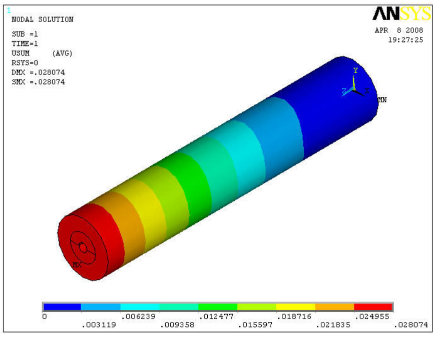


Fig. 5.4 Resultant displacement for 2 finger damper with no load

Fig. 5.4 shows the way resultant displacement behaves when constant load of 100N is applied .It shows that maximum displacement is only on the tip of the end mill and is 0.028074mm. Displacement is evenly distributed and the minimum value of displacement extends from the fixed end. Fig.5.5

shows the variation of von mises stress when a load of 100 N is applied. Maximum value of 14.739MPa on the upper surface of the end mill and reaches maximum near the fixed end of the end mill. Fig. 5.6 gives the variation in contact pressure. It has its maximum value between the end mill and the damper and the value is 0.69672MPa.

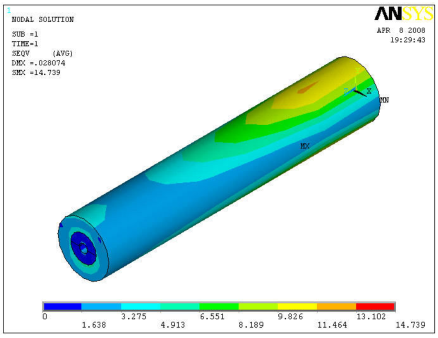


Fig. 5.4 von mises stresses for 2 finger damper with no load .

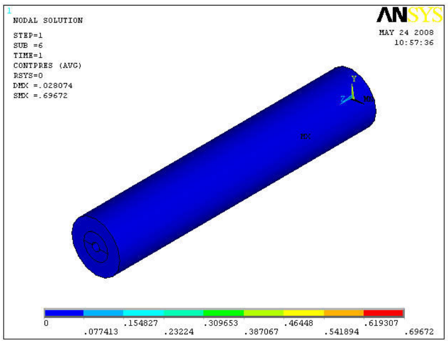


Fig. 5.4 Contact pressure for 2 finger damper with no load

5.2.THREE FINGER DAMPER

Damper is cut into three equal parts. Each finger makes an angle 120 degrees. Each finger is in contact with the other two fingers and the end mill. Fig 5.7 gives the over view of the variation of the resultant displacement. It is very even as there is no load applied. It has it's maximum value of 0.514E-3 at the tip and minimum at the fixed end. Fig. 5.8 indicates the variation of von mises stress. It is maximum where there is contact between damper and the end mill and the value is 6.465MPa. Minimum value of it is on the damper. The maximum value of contact pressure is 0.636588MPa and is between the end mill and the damper as shown in figure 5.9.

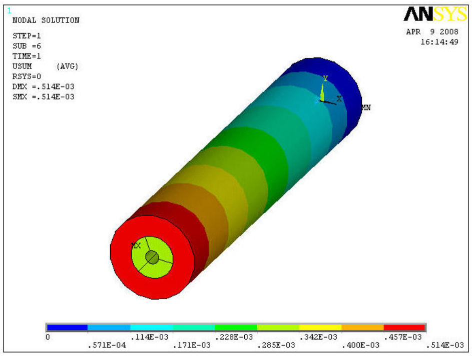


Fig 5.7 Resultant displacement for 3 finger damper with no load

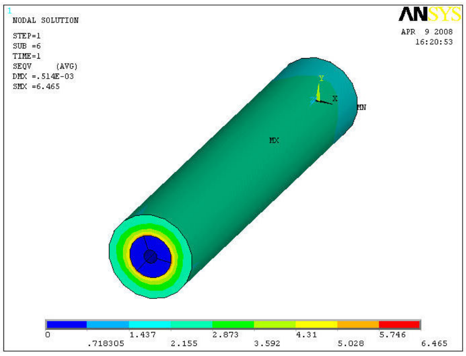


Fig 5.8 Von misses stress for 3 finger damper with no load

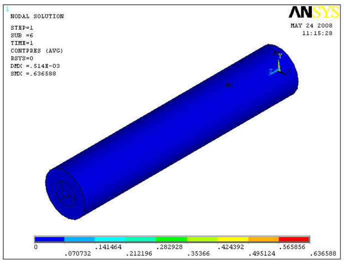


Fig 5.9 contact pressure for 3 finger damper with no load

A load of 100 N is applied at the end of the tool and the results are presented. Fig. 5.10 gives the indication of the variation of resultant displacement. The variation of resultant is evenly increased and later reaches it's minimum value before the fixed end. The maximum value which is at the tip of the end mill is 0.027881mm. Fig. 5.11 gives the variation of von mises stress. The maximum value of it is 14.379MPa and it occurs near the fixed and will be minimum for the damper. Contact pressure is maximum between the damper and the end mill and the value of it is 0.708735MPa. so it is not visible in figure 5.12.

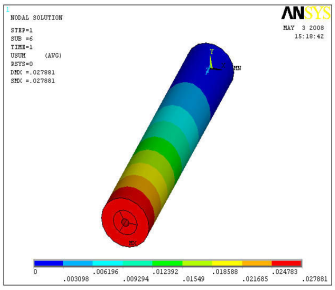


Fig 5.10 Resultant displacement for 3 finger damper with load

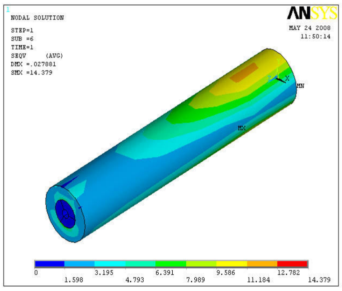


Fig. 5.11 Von mises stress for 3 finger damper with load

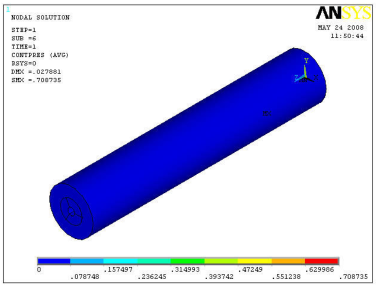


Fig.5.12 Contact pressure for 3 finger damper with load .

5.3. FOUR FINGER DAMPER

For four dampers the angle between each damper is 90 degrees and there is no gap between each damper there will be sliding friction which is going to be developed between these damper surfaces. Fig 5.13. indicates the variation of resultant displacement. It has very little increment in the displacement when compared with 3 finger dampers. The maximum value of resultant is 0.515E-3mm and is maximum at the tip of the end mill. Even the case of von mises stress is same as in the case of 3 finger damper. Maximum value of von mises stress in this case is 6.36MPa as shown in figure 5.14. The value of maximum contact pressure is decreased when compared to 3 finger damper; its value is 0.571245MPa as shown in figure 5.15.

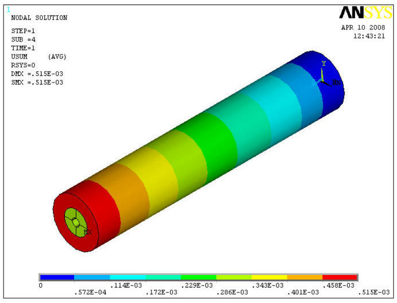


Fig.5.13. Resultant displacement for
4 finger damper with no load

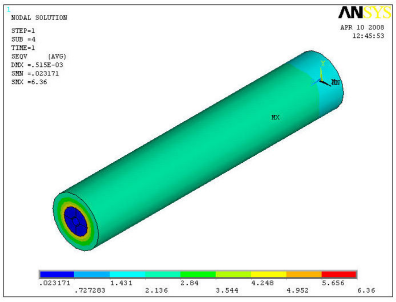


Fig.5.14. von mises stress for 4 finger damper with no load

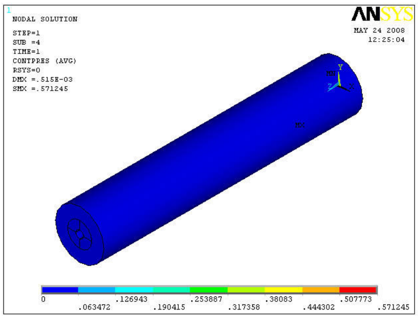


Fig. 5.15. Contact pressure for 4 finger damper with no load

The tool is tested under loaded conditions by applying a load of 100 N. Fig 5.16 gives the variation of resultant displacement. It varies evenly till the minimum value is reached. This minimum value of the resultant displacement is attained even much before the fixed end. The maximum displacement always remains at the tip of the tool but the value is 0.028025mm. Fig 5.17. indicates the variation of von mises stress. The maximum value of von mises stress is 6.36MPa and is maximum near the fixed end of the end mill. The value of von mises stress decreases from the fixed end of the end mill to the damper evenly and again increases from damper to end mill. Von mises stress is minimum for the damper. Contact pressure is decreased to much extent when compared to the previous value of three damper case. The maximum value of contact pressure is obtained between damper and the end mill which is 0.622258MPa as shown in fig 5.18.

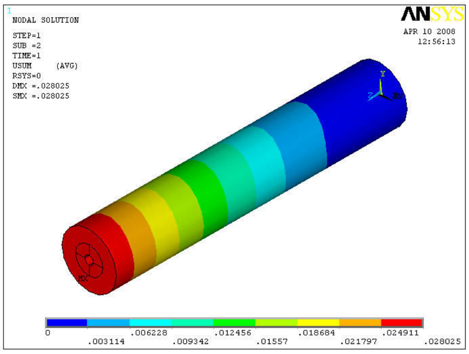


Fig. 5.16. Resultant displacement for 4 finger damper with load

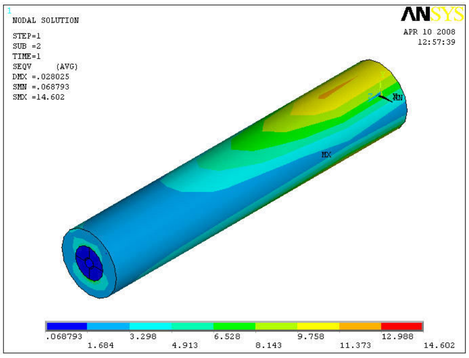


Fig. 5.16. von mises stress for 4 finger damper with load

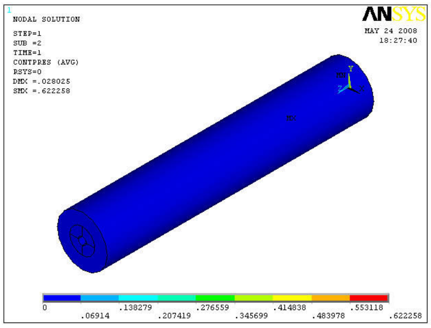


Fig. 5.18. Contact pressure for 4 finger damper with load .

5.4. FIVE FINGER DAMPER

When five finger damper is inserted into the end mill, the angle made by each damper is 72 degrees. This is the only case when an irregular angle is used. There is no gap between the dampers. There is sliding friction which is developed more between each damper and the end mill. Each damper is in contact with the other two dampers and the end mill. Fig 5.19. Shows the variation of resultant displacement. In this case the variation of resultant is very even than compared to all the other cases. The maximum resultant is at the tip of the end mill and minimum at the fixed end of the end mill. The value of the maximum resultant for this case is 0.505E-3mm. This is the minimum of all the displacement values when compared with all the finger dampers.

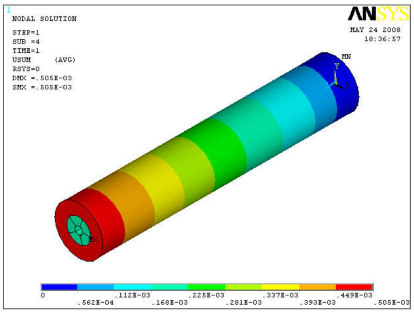


Fig 5.19. Resultant displacement for 5 finger damper with no load

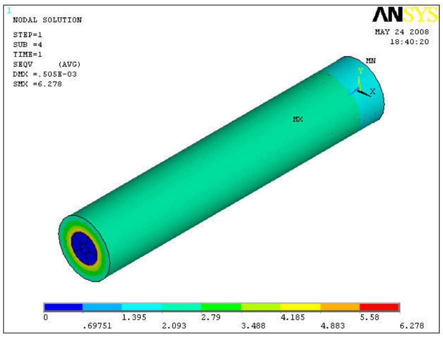


Fig. 5.20. Von mises stress for 5 finger damper with no load

Fig 5.20. indicates the variation of von mises stress. The maximum value is obtained where there is contact between the tool and the damper. The maximum value of von mises stress is 6.278MPa. Contact pressure is also developed at the centre where the end mill contacts with damper. The maximum contact pressure for this is 0.529316MPa. as shown in fig. 5.21. The tool is also tested under a load of 100N.Fig 5.22 gives the variation of resultant displacement. It is unevenly varied but has not much difference when compared with the previously. The maximum value of it is 0.028035mm. Von mises stress also does not change much compared to the previous value and it's maximum value is 14.591MPa as shown in figure 5.23.

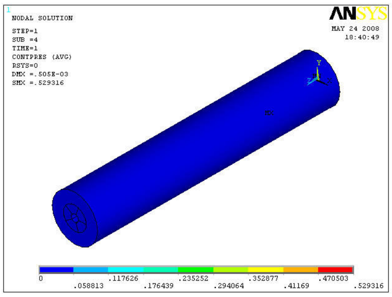


Fig. 5.21. Contact pressure for 5 finger damper with no load

Contact pressure is also developed at the centre where the end mill contacts with damper. The maximum contact pressure for this is 0.549958MPa.as shown in fig.5.24. The value obtained for this case very near approximately to the calculated analytical contact pressure.

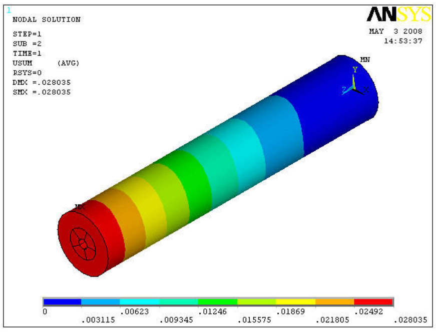


Fig. 5.22. Resultant displacement for 5 finger damper with load

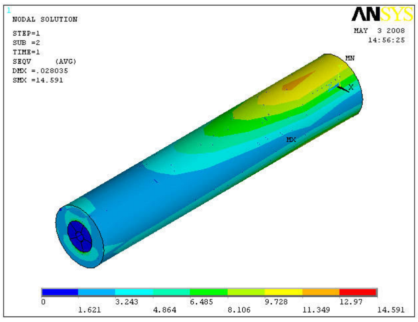


Fig.5.23. Von misses stress for 5 finger damper with load

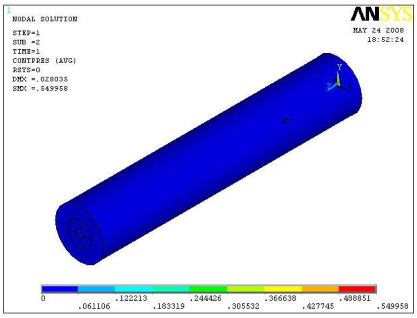


Fig. 5.24. Contact pressure for 5 finger damper with load

Figure 5.25. shows the variation of von mises stress is linear for both the cases but has up to 50% difference. Von mises stress is constant and very less when there is no load applied. Since no tool does not come in contact with the work piece, no additional stresses are developed apart from residual stresses developed during the rotation of the tool. But when angular velocity and load are applied von mises stress

has higher value. Figure 5.26 indicates the variation of total stress with number of fingers. . The resultant for these stresses is the total stress in the system.

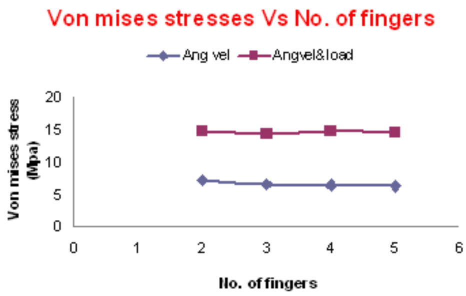


Fig. 5.25. Von mises stress Vs Number of fingers

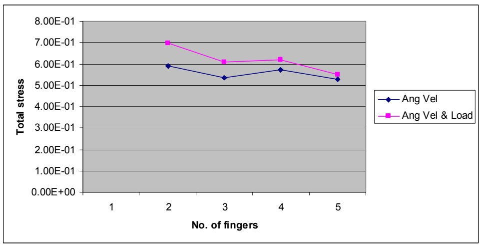
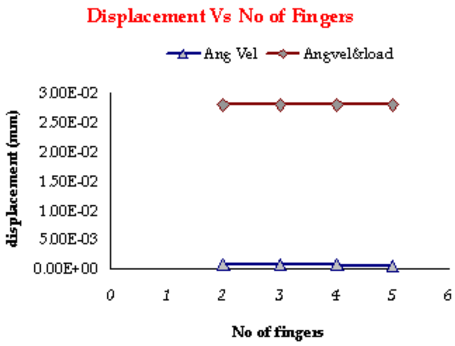
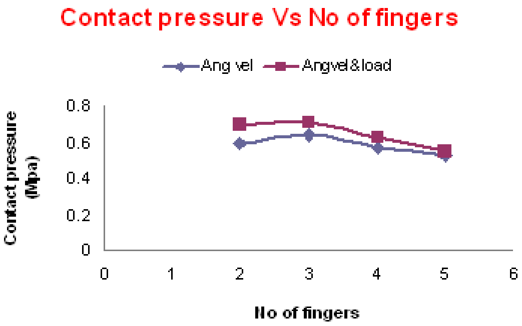


Fig. 5.26. Total stress Vs Number of fingers

Figure 5.26 indicates the variation of this total stress for the two different cases. It is clear that the total stress in the system changes with respect to the no of fingers. For both the cases as the number of finger increases the total stress variation becomes less and they coincide at a particular situation. Figure 5.27 indicates the variation of displacement as the number of fingers is increased. It can be observed that when there is no load applied to the end mill the displacement tends to be zero even if the number of fingers is 5; it is because end mill does not touch the work piece and so there is no displacement. The displacement is estimated to be approximately 0.028mm in case 2. The other important factor which has the main role in the non-linear contact problem is the contact pressure. The variation of contact pressure is not much, it ranges between 0.5 to 0.7. for both the cases. The contact pressure for both the cases tends to be equal as the no of fingers are increased. Contact pressure is developed for number of iterations. Figure 5.28 shows the way contact pressure is developed and for different number of iteration contact occurs.



. 5.27.Displacement Vs Number of fingers



5.28. Contact pressure Vs Number of fingers

6. NON LINEAR DYNAMIC ANALYSIS OF SINGLE DAMPER

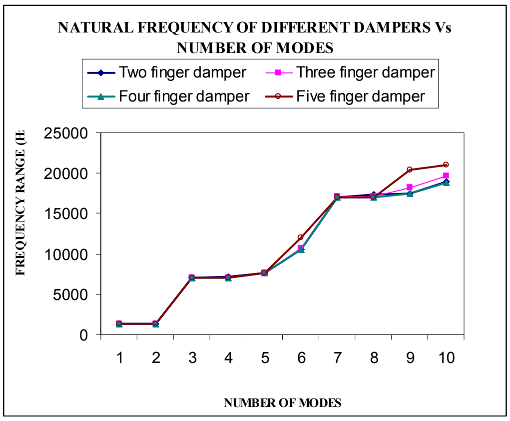


Fig. 6.1 Natural frequency of different dampers Vs number of modes

To reduce the vibrations of the tool, number of fingers of the damper is inserted into the end mill. By inserting the finger, natural frequencies are known and the amount of vibrations is known by the amount of damping effect. Natural frequencies are estimated by doing modal analysis in ANSYS. Effect of damping is estimated by harmonic analysis. Modal analysis is done to find the natural frequencies of two finger, three fingers, four fingers and five finger dampers. The natural frequencies are estimated for each case up to 10 modes. From fig 6.1 it is found that the natural frequency value for four finger damper is smaller than the other dampers.

7. CONCLUSIONS

Various parameters are analyzed to design the end mill cutter and the following conclusions were drawn.

- Displacement is maximum at the tool and work piece interface. Also resultant displacement decreases with increase in number of fingers.
- Von mises stresses were minimized by increasing the number of fingers.
- Contact Pressure between the contact surfaces is reduced as the number of fingers increased which further reduces the friction between surfaces.
- The amplitude of the vibrations is decreased which in turn decreased the frequency of vibrations.
- Four finger damper was optimal damper to reduce vibration of end mill cutter.

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