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Design and Analysis of Pneumatic Chuck with Diaphragm Input Parameters

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***Abstract*—With the advancement of cutting tool technology, machines need to have ultra-high speeds to make optimum use of the changing technology. To match this age of high speeds, work-holding for rotating machines need high gripping power, even at high cutting speeds. Since clamping chucks are most important components of tool machines to produce parts with high precision and concentricity, should have to be able to hold them securely and without distortion. Today, standard three-jaw power chucks remain the product of choice for use in the majority of turning applications. Since the diaphragm is critical component subjected to elastic deformation, the specialized spring steel made of the high-carbon or alloy type having high tensile properties is opted for designing the diaphragm. The ultimate objective is to design the diaphragm on the basis of its elastic limit range. For analysis utilize ANSYS software, it uses a preprocessor software engine to create geometry.**

Index Terms— **Diaphragm, Chuck, Specialized spring, Elastic deformation, Tetrahedral element.**

I. INTRODUCTION

Chucks are accessories that are used to hold a work-piece or cut down tool on a machine tool. The chuck is actually essential to a lathe's functioning as it fixtures the portion to the spindle axis of the work-holding machine. Lathe work-holding is an important but often over looked element of efficient manufacturing. However, an incorrect methodology of work-holding can potentially reduce the efficiency and quality of a chuck's performance, as well as pose a safety hazard. Today, standard three-jaw power chucks remain the product of choice for use in the majority of turning applications. But there are many applications where shops would do well to consider a chuck more specifically designed for the job. Picking the best work-holder can be a challenge for a lot of shops. While manufacturing managers or engineers may suspect that there is a better work-holder for the job, few feel that they have the in-house resources to thoroughly research "non-standard" alternatives. With the lean manufacturing environment that has become common practice today; few companies feel they can afford to keep a work-holding specialist on staff and so standard work-holding solutions prevail, even though many turning processes could be significantly improved with chucks more appropriately capable for the job at hand. What metalworking process managers should understand, however, is that finding better alternatives is not as difficult or expensive as they might suspect. A range of standard specialty chucks are available from manufacturers today that can solve a lot of the typical problems that shops encounter. And many of these models can be further tailored to an application with relatively minor (from a custom manufacturing standpoint) modifications to a standard design. Moreover, shops can help bridge the knowledge gap by drawing from the expertise of those who work with work-holding every day. Many chuck vendors are able and willing to help shops select which of these standard specialty chucks are best suited to any given application. With the advancement of cutting tool technology, machines needs to have ultra-high speeds to make optimum use of the changing technology. To match this age of high speeds, work-holding for rotating machines need high gripping power, even at high cutting speeds. Since most of the power operated chucks having sliding parts in the design, the accuracy and consistency of the chucks is doubtful in machining operations and varying dynamic conditions. In view of the above, it is intended to design a chuck having good accuracy and consistency and other desirable qualities to perform at maximum operating conditions. In most of the automotive lathes / CNC lathes the chucks are run on pneumatic power for work-holding. The design is carried out for standard chuck size of 6" dia. actuated by pneumatic power actuation. There are two basic jaw actuation systems the "wedge or sleeve" system and the "lever" system based on which so many chucks are designed in work-holding. Present design of this dissertation work is associated with neither sleeve system nor lever system of actuation. The third type jaw actuation is conceptualized which is called as Diaphragm operated system of actuation.

In study carried out by Jakub Javorik et. al [1], Analysis of mechanical behaviour of a rubber diaphragm inside a pneumatic valve and the FEM analysis appears as a very appropriate tool for this work. The hyper elastic parameters of the elastomer material of valve diaphragms were measured. Analyses of the diaphragms in working conditions were carried out. Considering the results of these analyses the new shapes of the diaphragms

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were designed and were verified again by the numerical analyses. A study by A. Cellatoglu et. al[2], Thin metallic shallow spherical diaphragms are being used for measuring pneumatic pressure in process industries. The drift in vertex realized due to application of pressure is transformed into electrical signal and this is calibrated for pressure. We now propose a modified structure for the pressure cell by having double ended shallow spherical shells embedded with spherical corrugations as to enhance the sensitivity to a greater extent. By having dual such installation in the structure of the pressure cell it concedes further increase in sensitivity. The construction details of the diaphragm structure, theory and analysis to assess the performance are presented. In a study by A. Senkus, E. et. Al., [3], the manufacturing industry has been trying to attain a required cutting performance of high precision, fast productivity and less maintenance cost. Vibrations during machining can be a serious problem influencing manufactured parts quality, precision, tool service life, lathe performance and cutting rates. This paper presents an analysis of the cutting process using modal methods. Static and dynamic deformations of lathe collet chuck have a significant impact on cutting process stability, which affects the quality of manufactured parts and productivity rates. Utilising a modal analysis, a mathematical model of chucks dynamics, which consist of a number of mode shapes each with natural frequency and modal damping, has been developed. Modal analysis and experimental measurements were performed for CNC lathe collet chuck.

II. MATERIAL AND METHODS

A. Meshing the Diaphragm with Solid 92, 3-D and 10-Node Tetrahedral structural solid element

The surface model required for this FE modeling has been developed in ANSYS Software. The ten nodded tetrahedral element is most commonly used element for modeling of solid structure. The use of this element is limited to simple geometries and pre-requite is error free. The user has to just select the volume and software automatically carries out meshing as specified element length, quality criteria etc. The main advantage of tetra meshing is very quick and it doesn't need much meshing efforts. This element in ANSYS is simply known as SOLID 92. It has a quadratic displacement behavior and is well suited to model irregular meshes (such as produced from various CAD/CAM systems). The element is defined by ten nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element also has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

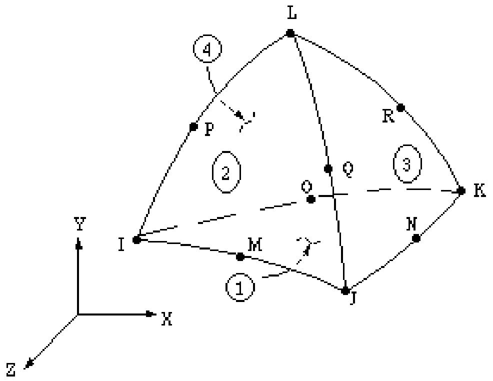

Fig 1. SOLID92, 3-D, 10-Node Tetrahedral Structural Solid

(i) Input Data

The geometry, node locations, and the coordinate system for this element are shown in the Figure. Beside the nodes, the element input data includes the orthotropic material properties. Orthotropic material directions correspond to the element coordinate directions. Pressures may be input as surface loads on the element faces as shown by the circled numbers on the figure. Positive pressures act into the element. Temperatures and fluencies may be input as element body loads at the nodes. A summary of the element input is given in Table: 1

Table 1. SOLID92 Input Summary

Element Name	SOLID 92
Nodes	I, J, K, L, M, N, O, P, Q, R

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DOF	UX, UY, UZ
Real Constants	None
Material Properties	EX, EY, EZ, ALPX, ALPY, ALPZ, (PRXY, PRYZ, PRXZ or NUXY, NUYZ, NUXZ), DENS, GXY, GYZ, GXZ, DAMP
Surface Loads	Pressures: face 1 (J-I-K), face 2 (I-J-L), face 3 (J-K-L), face 4 (K-I-L)
Body Loads	Temperatures: T (I), T (J), T (K), T (L), T (M), T (N), T (O), T (P), T (Q), T (R) Fluencies: FL (I), FL (J), FL (K), FL (L), FL (M), FL (N), FL (O), FL (P), FL (Q), F L (R)
Special Features	Plasticity, Creep, Swelling, Stress stiffening, Large deflection, Large strain, Birth and death, Adaptive descent.

(ii) Output Data

The solution output associated with the element is in two forms:

- nodal displacements included in the overall nodal solution
- additional element output

Several items are illustrated in Figure below. The element stress directions are parallel to the element coordinate system. The surface stress outputs are in the surface coordinate system and are available for any face. The coordinate system for face JIK is shown in Figure: 2. the other surface coordinate systems follow similar orientations as indicated by the pressure face node description.

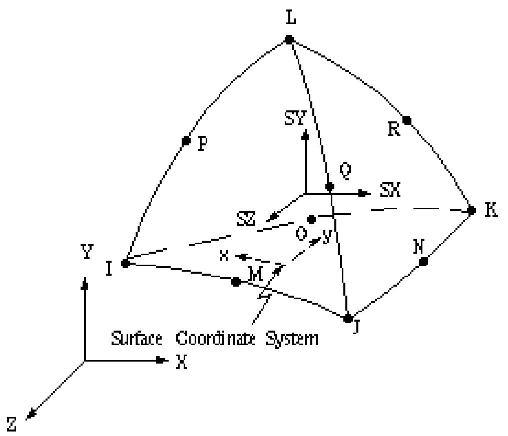

Fig 2. SOLID92 Stress Output

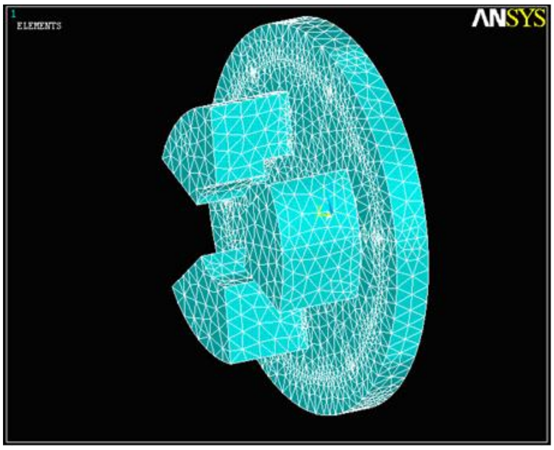

Fig 3. SOLID 92 element meshing

B. Data Table for Spring Material

Since the natural spring tension of the diaphragm made out of specialized material has to provide sufficient grip force for clamping and unclamping the work-piece, the spring material should be stiff enough and elongate along axial direction on which FEM load is applied to facilitate radial clearance at the jaws as well. Since the diaphragm has to undergo more amounts of stresses, the mechanical and physical properties are tabulated below.

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Table 2. The Spring Material Physical Properties

Spring steel material	Melting temperature (°c)	Density (Kg/mm ^{3})	Electrochemical potential (v)
C- 0.45-0.55, Mn-0.50-0.80, Cr- 0.80-1.10 V- 0.15-0.18	1540	$7.85*10^{-6}$	-0.45

Table 3. The Spring Steel Mechanical Properties

Spring steel material	Young's modulus (N/mm^2)	Poisson's ratio	Elastic Limit (N/mm^2)	Ultimate tensile stress (N/mm^2)
C- 0.45-0.55 Mn- 0.50-0.80 Cr- 0.80-1.10 V- 0.15-0.18	206.01×10^3	0.3	1239.9 – 1589.2	1379.5-1724.4

C. Cylinder Ratings

Air cylinders are recognized as the final module in a pneumatic, compressed air control or in any power system. Air cylinders, or pneumatic cylinders, are tools which switch compressed air power in to a usual mechanical or automatic energy. This mechanical energy generates linear or rotating motion. In this way, the air cylinder works as an actuator in any pneumatic system, so it is as well as identified as a pneumatic linear actuator. The air cylinder comprises of steel or could be of stainless steel piston, a piston rod, a cylinder container and including end covers. As compressed air progresses in to the air cylinder, it moves forward to the piston along the length of the air cylinder. Compressed air or a coil, situated at the rod end of the cylinder, moves the piston back. Valves are the one that control the pour of the compressed air to the cylinder.

Cylinder size= 6" (152 mm of binary acting)
Maximum air pressure= 150 psi = 1.034 N/mm^2
Allowed air pressure for actuation of the chuck = 0.7845 N/mm^2 (Designed load)
Draw tube force at pressure load of 0.7845 N/mm^2 = 8352.52 N

D. 2D Model of Proposed Diaphragm

The draw tube with actuates the Diaphragm which in turn transfer the draw tube force to the top jaws, acting as a integral part of the diaphragm. The diaphragm is actuated with fine adjustment of different pressures by a system of air cylinders; draw tube, spindle and adapter plate. The diaphragm resembles the Belleville disc spring with varied uniform thickness on one side and flattened surface biased to accommodate integral part of the jaw base on which chuck jaws are mounted by means of fasteners. The 2D model with variable dimensions designated as **A, B, C, R, R1, and R2** as shown in figure 4 are found to be crucial input parameters in designing the diaphragm which is stated to be the critical component in this dissertation work. The diaphragm is subjected to different pressure loads not exceeding 0.7845 N/mm^2 which is the designed load for diaphragm actuation. Since the diaphragm is critical component subjected to elastic deformation, the specialized spring steel made of the high-carbon or alloy type having high tensile and resilience properties is opted for designing the diaphragm. By means of above parameters, the three dimensional model of diaphragm is modeled and meshed with 10 node, SOLID 92 element by using ANSYS preprocessor. Then it uses solution routine to apply loads to the meshed geometry. Finally it outputs desired results in post-processing. The analysis procedure is continued till the desired results are achieved.

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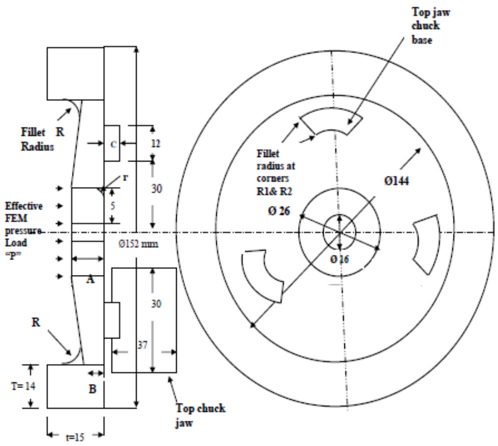

Fig 4. 2D Model of proposed diaphragm with integral jaw base and jaws

Rated air cylinder pressure=150 psi = 1.304 N/mm^2

At 0.7845 N/mm^2 pressure the draw tube force = 8352.52 N

Pressure load = 0.7845 N/mm^2 (Designed load for actuation)

Pressure load to be applied on the FEM model= 8352.52/330 = 25.30 N/mm^2

E. Boundary Conditions

(i) Constraints

The diaphragm with jaws is connected to chuck body with the help of fasteners. For the purpose of analysis the diaphragm base is constrained at critical position in all degrees of freedom {ALL DOF}. This is done by selecting the surface of the diaphragm base and arresting the all displacements at these nodes. i.e. U_x, U_y, U_z, R_x, R_y, R_z. The following figure shows the constraints to the model. For analysis purpose 1/3 part of Diaphragm as shown in figure: 5 is taken by applying the symmetric boundary conditions in order to reduce the processing time as against full diaphragm as shown in figure: 6

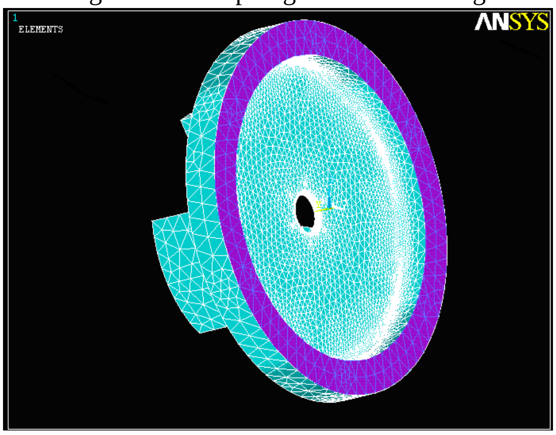

Fig 5. Boundary Conditions for Full Diaphragm

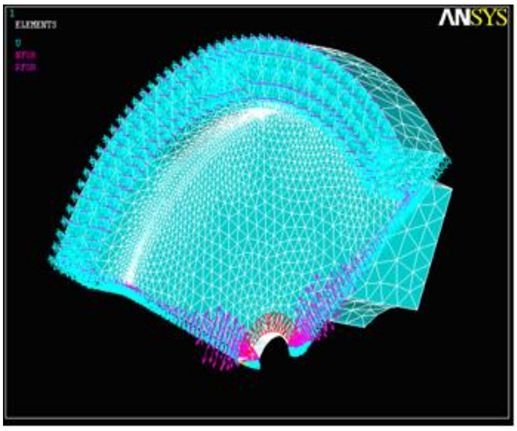

Fig 6. Boundary Condition for 1/3 of Diaphragm

III. RESULTS AND DISCUSSION

The 2D model with variable dimensions designated as **A, B, C, R, R1, and R2** are input parameters in designing the diaphragm. In each analysis the three dimensional model of diaphragm is drawn by using ANSYS modeling followed by ANSYS procedure as follows.

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Table 4. Number of Analysis of Diaphragm Design in Tabulated Form

Number of analysis	Dimensions in mm(variables)						Von-Mises stress in N/mm^2	FEM Load at Center in N/mm^2	Elastic limit in N/mm^2	Radial clearance of jaw end "ΔY" in mm
	A	B	C	R	R1	R2				
1.	2.0	1.5	1.0	-	-	-	6408.04	25.30	1239.9 – 1589.2	4.016
2.	2.0	1.5	1.0	-	-	-	6408.04	25.30	1239.9 – 1589.2	4.016
3.	2.5	2.0	1.0	-	-	-	4266.09	25.30	1239.9 – 1589.2	1.948
4.	2.6	2.0	1.0	-	-	-	3524.88	25.30	1239.9 – 1589.2	2.195
5.	2.7	2.2	1.0	5.0	-	-	3052.91	25.30	1239.9 – 1589.2	1.507
6.	2.8	2.1	1.0	3.0	3.0	-	1984.41	25.30	1239.9 – 1589.2	1.626
7.	3.0	2.0	1.5	2.0	3.0	2.0	1961.80	25.30	1239.9 – 1589.2	1.588
8.	3.5	2.2	2.0	1.5	3.0	3.0	1513.50	25.30	1239.9 – 1589.2	1.114
9.	3.6	2.4	1.5	1.5	3.0	5.0	1228.61	25.30	1239.9 – 1589.2	0.896

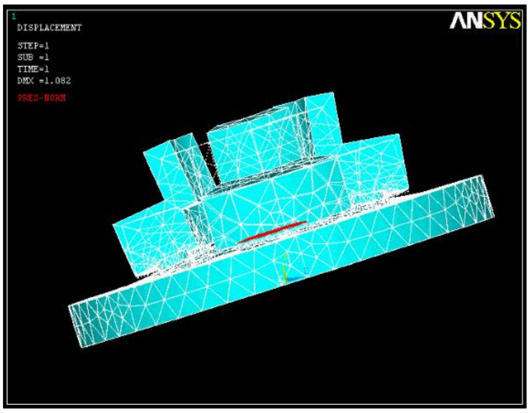

Fig. 7: Opening Position of top jaws for Work-piece loading

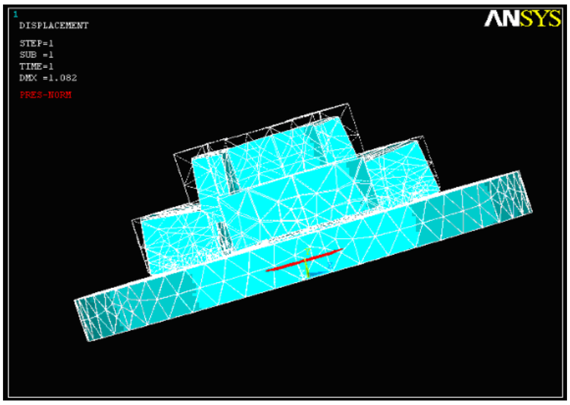

Fig. 8: Closing Position of Top Jaws after Work- piece loading

A. Final Dimensions of the Diaphragm by FEM Analysis

The final dimensions of the diaphragm thus obtained by means of FEM analysis is tabulated in Table: 5 below. The functionality of various dimensions with notations of the diaphragm is described to better understand the design of the diaphragm which is critical component in this dissertation work**.**

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Table 5. Final Dimensions of the Diaphragm and its Functionality in Tabulated Form

Name of the Dimensions	Notations	Value	Functionality
Outside Diameter of the Diaphragm	ϕ	152mm	Design and Analysis carried out on 6" dia. Diaphragm chuck.
Maximum thickness of the diaphragm at the center	A	3.8mm	Value obtained by FEM analysis.
Minimum thickness at the inside flange dia. of the diaphragm	B	2.6mm	Value obtained by FEM analysis.
Fillet radius at the inside flange dia. of the diaphragm	R	1.5mm	Value obtained by FEM analysis. Flexible application and to maintain stiffness of diaphragm.
Fillet radius at center hole of the diaphragm	r	0.75mm	Value obtained by FEM analysis. To accommodate push rod for actuation of the diaphragm.
Jaw base fillet at top corner	R1	3.0mm	Value obtained by FEM analysis. To accommodate top jaws and fixed by M6 fastener from inside of the diaphragm.
Jaw base fillet at top corner	R2	6.0mm	Value obtained by FEM analysis. To accommodate top jaws and fixed by M6 fastener from inside of the diaphragm.
Flange of Diaphragm radial thickness	T	14mm	To accommodate M8 fastener head.
Flange of Diaphragm axial thickness	t	15mm	To accommodate M8 fastener and to fix on chuck body.
Thickness of the Jaw	C	3mm	Value obtained by FEM analysis.

IV. CONCLUSION

Considering the important features in work-holding is carried out to design, development and analysis of a diaphragm incorporated in the chuck design for particular applications in addition to the standard chuck applications. In advent of sophisticated FEA tools such as ANSYS which has been extensively used in this dissertation work to design and development of a diaphragm with integrated Jaws to hold the work-piece satisfying all and additional requirements. A few FEA runs by ANSYS (analysis software) necessity to modify the design and redesign at a deeper level in identifying the right travel limit for diaphragm design to avoid pre-mature failure and ultimately deduced to find a solution to specify the stipulated objectives as above.

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