THESIS

ON

ULTRASONIC MACHINING SYSTEM-MODELING, ANALYSIS, EVALUATION AND SELECTION

Submitted in partial fulfillment of the requirement for the award of degree of

MASTER OF ENGINEERING
IN
PRODUCTION & INDUSTRIAL ENGINEERING

Submitted by

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DECLARATION

I hereby declare that the thesis entitled **"Ultrasonic Machining System - Modeling, Analysis, Evaluation and Selection"** is an authentic record of my study carried out as requirement for the award of degree of **Master of Engineering (Production and Industrial Engineering)** at Thapar University, Patiala under the guidance of **Dr. V.P.Agrawal**, Visiting Professor, Department of Mechanical Engineering, Thapar University, Patiala during **July 2012 to July 2013**. The matter embodied in this report has not been submitted in part or full to any other University or Institute for the award of any other degree.

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This is to certify that above declaration made by the student concerned is correct to the Best of my knowledge and belief.

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ABSTRACT

Non conventional is the process used to overcome the drawbacks of conventional process. Two main tool techniques i.e. Graph Theoretic approach and MADM i.e. TOPSIS and Graphical methods i.e. Line Graph method and Spider Diagram Method are used in ultrasonic machining system. In this thesis work, an attempt is made to increase an integrated systems model for the creation of ultrasonic machining system in terms of its constituent and interaction between the constituent and process etc, using graph theory and matrix algebra. The ultrasonic machining system is first modeled with the help of graph theory, then by a variable adjacency matrix and then by permanent function. The permanent function is used to bring out structural analysis of ultrasonic machining system by correlating the different system with its structure. A physical representation has been related with each term of permanent function. Different structural parameters of ultrasonic machining system are identified to develop a graph theoretic model, a matrix model and a permanent function model of an ultrasonic machining system. It is useful for better understanding, comparison, ranking and optimum selection of ultrasonic machining system from the alternates of ultrasonic machining systems available in the global market, the multiple attribute decision making problems is solved by "TOPSIS" (Technique for Order Preference by Similarity to Ideal Solution). The techniques convert the database into knowledge base by taking into consideration normalization, relative weights, positive benchmark and negative benchmark for ultrasonic machining system. The selection procedure by TOPSIS allows short listing of ultrasonic machining parameter from a large number of parameter by using elimination search. The rank of a particular ultrasonic machining system is calculated by TOPSIS method and Graphical method with respect to the best possible ultrasonic machining system, say positive benchmarked for particular usage and then ranking was done based on comparison between TOPSIS and Graphical Method i.e. Line Graph and Spider Diagram method to get the overall best ranked ultrasonic machining system. The final decision is made by the user by taking into the consideration various factors i.e. Economic consideration, Availability etc. MADM approach provides technique for selection of best ultrasonic machining system for application under consideration. MADM and Graph theoretic Approach has been demonstrated with illustrative example.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Sr. No.	Abbreviation	Description
1	μ	Micro
2	RUM	Rotary Ultrasonic Machining
3	RUSM	Rotary Ultrasonic Machining
4	FEM	Finite Element Method
5	SiC	Silicon Carbide
6	Al_2O_3	Alumina
7	PCD	Poly Crystalline Diamond
8	FEA	Finite Element Analysis
9	PMMA	Polymethyl Methacrylate
10	UAT	Ultrasonic Assisted Turning
11	CT	Conventional Turning
12	UAG	Ultrasonic Assisted Grinding
13	CG	Conventional Grinding
14	CUSM	Chemical assisted Ultrasonic Machining
15	UVC	Ultrasonic Vibration Cutting
16	Ra	Surface Roughness
17	TWR	Tool Wear Rate
18	MRR	Material Removal Rate
19	ABC	Artificial Bee Colony
20	HS	Harmony Search
21	PSO	Particle Swarm Optimization
22	GA	Genetic Algorithms
23	WSN	Weighted signal to noise ratio method
24	GRA	Grey Relational Analysis method
25	MRSN	Multi response signal to noise ratio method
26	TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
27	MADM	Multiple Attribute Decision Making

CHAPTER 1

INTRODUCTION

1.1 Introduction

Nontraditional machining is a type of machining process that is used to remove excess material by using various types of energy i.e. mechanical, thermal, electrical, or chemical energy (or combinations of these energies). In this type of machining process tool is not in contact with the work piece.

Ultrasonic machining is a nontraditional machining process. It is grouped under mechanical group nontraditional machining process. It is based on impact erosion process. Ultrasonic machining process is an abrasive process and material removal is purely mechanical. The process equipment consists of vibrating horn, a tool part, abrasive slurry and work piece. Ultrasonic machining is a process in which abrasive particle in a slurry with water are presented to the work surface in the presence of the ultrasonically vibrating tool. Ultrasonic machining is a mechanical material removal process used for machining non conductive, hard or brittle work material by using shape tool high-frequency mechanical motion and an abrasive slurry. Ultrasonic machining is used to machine all materials which are not softer than 40HRC. USM is also known as ultrasonic drilling; ultrasonic abrasive machining; ultrasonic cutting; ultrasonic dimensional machining; slurry drilling.

The machining parameters which affect the performance parameters can be clearly understood with the help of Cause and effect diagram. To improve machining efficiency and accuracy, it is necessary to understand the relationship between machining parameters and performance parameters. The material removal rate and tool wear rate was calculated by noting down the time of machining. Surface roughness are found with the help of the surface roughness tester.

$$\text{Material removal rate} = \frac{W_1 - W_2}{\rho * t}$$

Where W_1= Initial weight of the material

W_2= Final weight of the material

ρ = density of the work piece material

t= time of machining

$$\text{Tool wear rate} = \frac{w_1 - w_2}{\rho * t}$$

Where w_1= Initial weight of the tool

w_2= Final weight of the tool

ρ= density of the tool material

t= time of machining

The Ultrasonic machining process doesn't use cutting tools and do not create residual stresses in the work piece. Ultrasonic machining is often used in combination with other chip less machining techniques, such as electric discharge machining (EDM), in the manufacturing of precision components.

The term ultrasound is used to describe the vibration waves having a frequency above the hearing range of normal human ear i.e. beyond 20 kHz. The audible range of vibration is the one which the human ear perceives i.e. in the frequency range of 20Hz to 20 kHz, the ultrasonic range of vibration lies above this i.e. Frequency beyond 20 kHz. There is no physical difference between the upper audio range 20 Hz- 20 kHz and ultrasonic range 20 kHz- 200 kHz. Both the range of frequencies of certain intensities of sound will be heard as loud noise by the human ear and can permanently damage the hearing system. Ultrasonic frequencies of the same intensities of sound cannot be heard by the human ear and they are less harmful. Ultrasonic frequencies provide satisfactory working conditions and hence they are alone used for the material removal purposes.

Fig. 1.1 Stationary Sonic Mill Ultrasonic Drilling Machine
[Machine Tool Lab., TU, Patiala]

1.2 Need for Ultrasonic Machining

The process is regarded as competitive only when an operation cannot be practically and economically performed by conventional machining equipment. The ultimate value of USM lies in the ability to do work that cannot be practically accomplished in any other way as the USM is non chemical and non thermal process.

USM is used to machine very hard and not easy to machine material by conventional methods. Glass is a material not easy to machine by any means but excellent result has been obtained with the help of ultrasonic machining process.

1.3 Principle of USM process

Fig 1.2 shows the principle of USM. In fig 1.2, a tool is vibrating at an ultrasonic frequency, typically 20 kHz over the work piece. The tool is fed gradually with uniform force. Between tool and work piece machining region is deluged with slurry with the help of nozzle; this slurry is the mixture of abrasive and water. As the tool vibrates over the work piece , the abrasive particle impact on work piece thus removing material in the form of small wear particles that are carried away by the abrasive slurry. The tool material, being hard and ductile, wears out at a much slower pace.

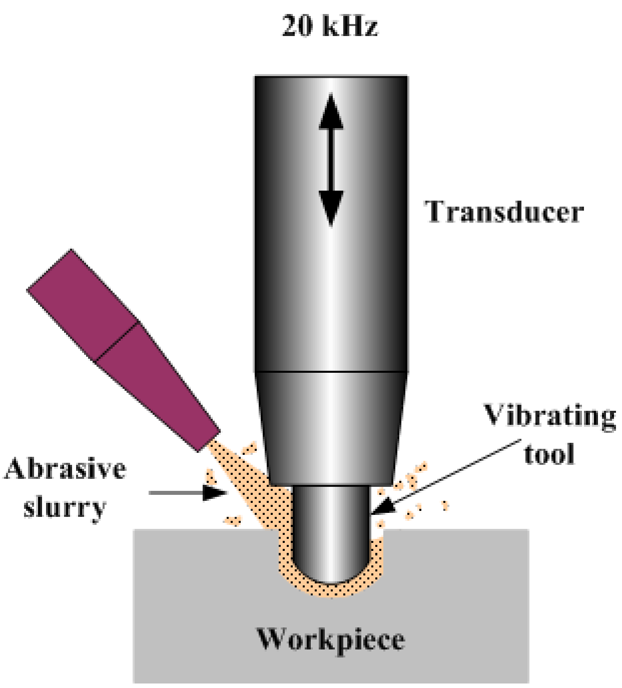

Fig1.2:- Principle of USM [47]

1.4 Mechanism of material removal of USM

USM is used for machining brittle work material. Material removal occurs as the hard abrasive grit comes in contact with the brittle work material. As the tool vibrates abrasive particle indents the work material. During indentation, due to hertzian contact stresses cracks would develop just below the contact site and as the indentation goes on, cracks would propagate due to increase in hertzian stresses thus leading to brittle fracture of work material under each interaction between abrasive grit and work piece (Fig. 1.3). The tools should be made of hard and ductile materials like steel, stainless steel so that groove by coarse grit does not lead to fragile rupture

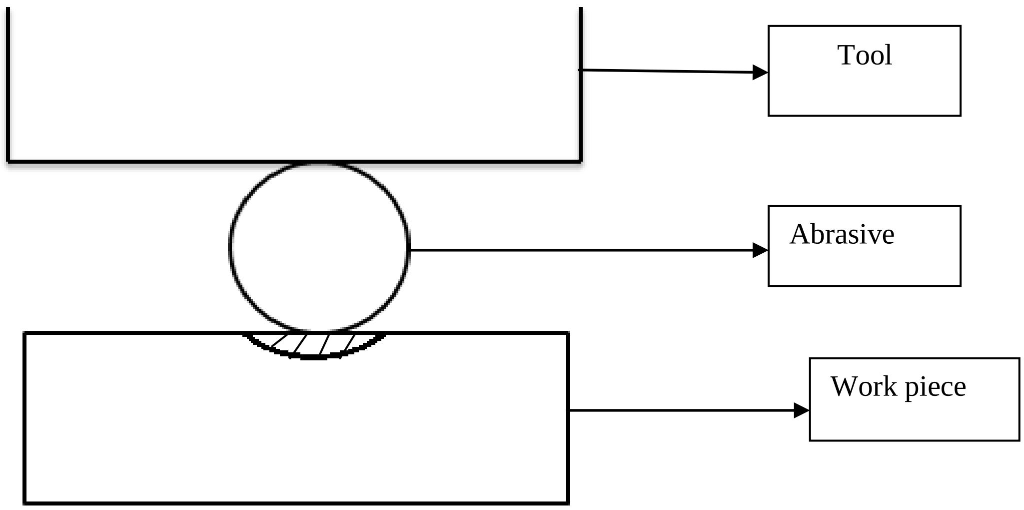

Fig 1.3:- Mechanism of material removal of USM [48]

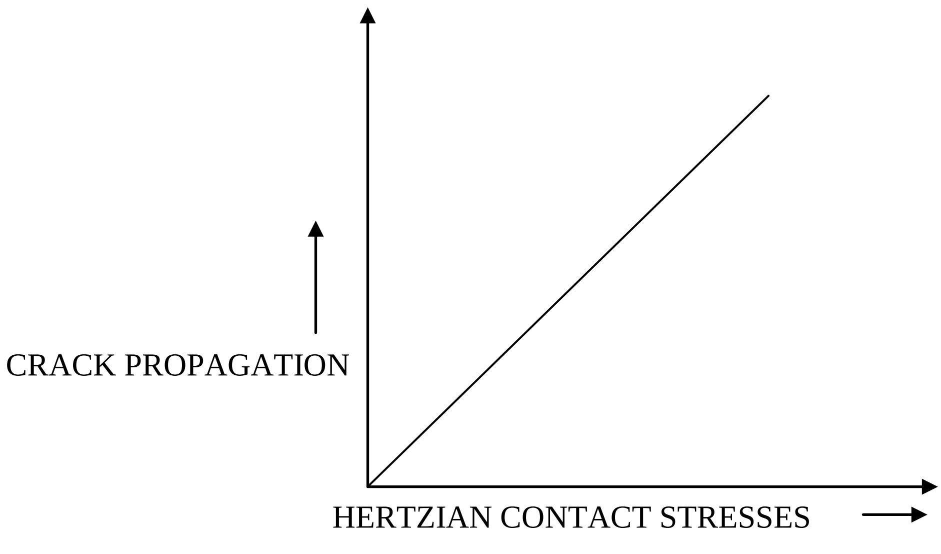

Fig 1.4:- Graphical representation showing brittle fracture of the material in USM process

1.5 Micro USM with tool vibration

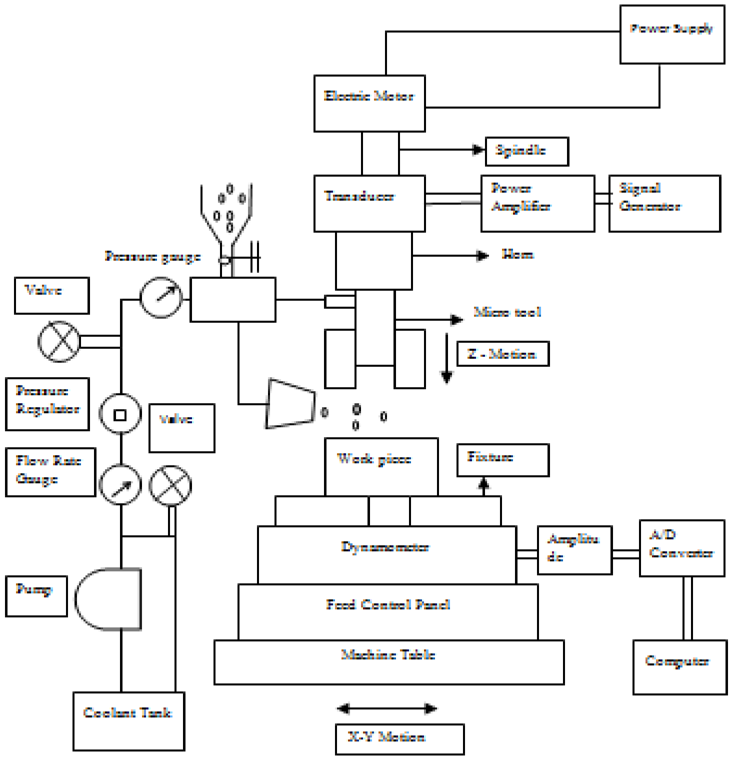

Fig 1.5:- Schematic Diagram of Micro USM with tool vibration

This system mainly consists of an ultrasonic spindle system, data acquisition system and slurry supply system.

1.5.1 Ultrasonic Spindle System

The ultrasonic spindle system consists of ultrasonic spindle, power supply and motor speed controller. The power supply converts low frequency (50 Hz) electrical power to high frequency (approximately 20 kHz) AC output. This is fed to piezoelectric transducer located in the ultrasonic spindle. The ultrasonic transducer converts the electrical input to mechanical vibrations. These vibrations are then transferred to horn to amplify the vibration to the required amplitude of around 15-50 µm and transfer the vibration to the tool. The motor attached at the top of ultrasonic spindle supplies rotational motion to the tool and different speeds can be obtained by adjusting the motor speed controller.

1.5.2 Data Acquisition System

The fixture to hold the work piece was mounted on dynamometer that was attached to machine table via the feed control panel. During rotary ultrasonic machining, the cutting force along the feed path was measured by a dynamometer. The dynamometer was mounted on the machine table via feed control panel and beneath the work piece. The electrical signal from dynamometer is transformed into a numerical signal by A/D converter. Then the numerical signals to measure the cutting force were displayed and saved on the computer.

1.5.3 Slurry Supply System

Coolant tank is used to store water, which is transferred to the upper system using pump. Flow rate gauge is used to maintain the flow of the coolant, while pressure regulator is used to maintain the required pressure. The control valve is used to keep the coolant supply on or off. Then pressure gauge is attached at the coolant supply end to measure the pressure of the supplied coolant. A mixing tank is then incorporated for mixing coolant and slurry in a certain ratio as per the requirement. Then the mixture of abrasive and coolant is supplied through nozzle via pipe to maintain a desired speed of the flow.

1.6 Micro USM with work piece vibration

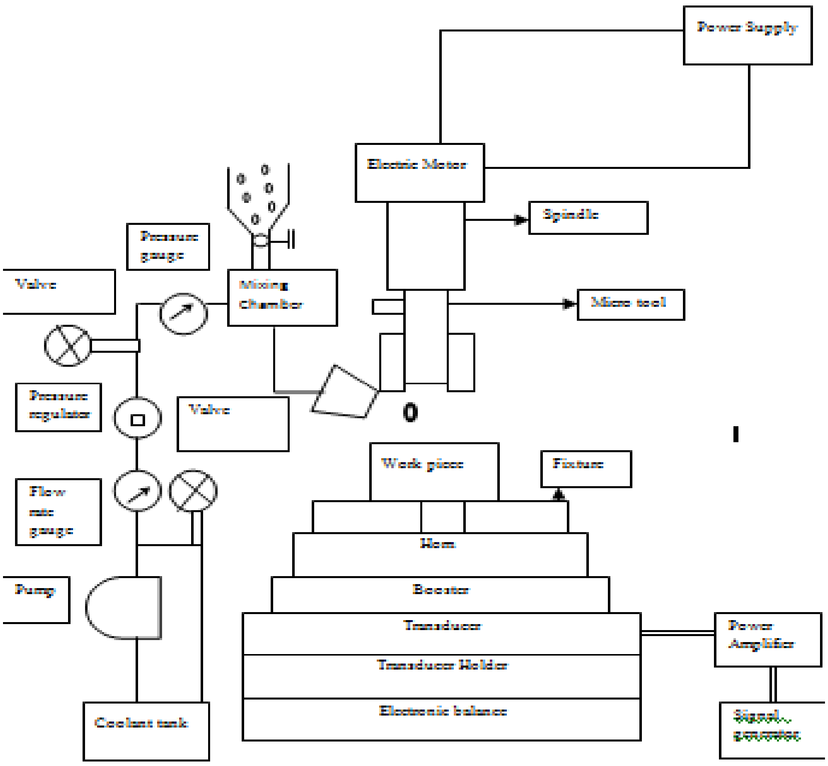

Fig. 1.6:- Schematic Diagram of Micro USM with work piece vibration

This system consists of power supply system, slurry supply system and work piece vibration system.

1.6.1 Power Supply System

This system consists of a power supply, electric motor, spindle and tool. The motor is operated as it gives an electrical signal through the power supply. The tool is rotated through electric motor via the spindle. The motor attached at the top of ultrasonic spindle supplies rotational motion to the tool and different speeds can be obtained by adjusting the motor speed controller. Diamond abrasives are embedded at the periphery of the tool.

1.6.2 Work Piece Vibration System

This consists of electronic balance, transducer holder, transducer, booster, horn, fixture and work piece. The tool feed motion is controlled by measuring the machining load using electronic balance. Transducer holder is attached to electronic balance which is used to hold the transducer. The transducer is given vibration through signal generator via power amplifier. The ultrasonic transducer is used in USM to convert electric signal into mechanical vibrations. This vibration is transferred to the work piece through the horn via booster by amplifying the vibration produced in the transducer.

1.6.3 Slurry Supply System

Coolant tank is used to store water, which is transferred to the upper system using pump. Flow rate gauge is used to maintain the flow of the coolant, while pressure regulator is used to maintain the required pressure. The control valve is used to keep the coolant supply on or off. Then pressure gauge is attached at the coolant supply end to measure the pressure of the supplied coolant. A mixing tank is then incorporated for mixing coolant and slurry in a certain ratio as per the requirement. Then the mixture of abrasive and coolant is supplied through nozzle via pipe to maintain a desired speed of the flow.

Table 1.1:- Difference Between Micro USM with Tool and Workpiece Vibration

Micro USM with tool Vibration	**Micro USM with work piece vibration**
More tool wear	Less tool wear
Cutting force along the feed direction can be measured by the use of the dynamometer	Cutting force cannot be measured

1.7 Important Process Parameters of USM Process

1.7.1 Ultrasonic Power Supply

It converts low frequency (50/60 Hz) electrical power to high frequency (approximately 20 kHz) and this electrical signal is supplied to the transducer. The main requirements of the generator are:-

- Reliability and Durability
- Efficiency
- Simplicity in design and low cost
- Compact and easy to operate
- Controlled power output

Fig. 1.7 Power Supply Generator

[Machine Tool Lab., TU, Patiala]

1.7.2 Ultrasonic Transducer

Transducer is a device that converts one form of energy into another. The ultrasonic transducer converts the electrical energy into mechanical motion. There are two types of transducer based on the principle of operation:-

1. Piezoelectric Transducer
2. Magnetostrictive Transducer

1.7.2.1 Piezoelectric Transducer

The active element is the heart of transducer as it converts electrical energy into mechanical vibrations and vice versa. The active element is polarized material (where some part of molecules are positively charged while some are negatively charged) with electrodes attached to two of its opposite faces .When an electric field is applied across the material , polarized molecules will align themselves with electric field . This alliance of molecule will cause material to change its dimensions. This incident is known as electrostriction. In addition a permanent polarized material such as quartz (SiO2) or barium titanate (BaTiO3) will produce an electric field when material dimension changes as the mechanical force is applied. This incident is well-known as the piezoelectric effect. Piezoelectric transducer reveals elevated electromechanical change efficiency of around 95 %.

1.7.2.2 Magnetostrictive Transducer

The Magnetostrictive transducer is a device which converts magnetic energy into mechanical energy and vice versa. Electrical signal generated is amplified using power amplifier which is then transferred to the transducer .Transducer consists of coils. As signal is supplied to transducer magnetization and demagnetization of coil take place due to which vibrations are produced. These vibrations are sent to horn.

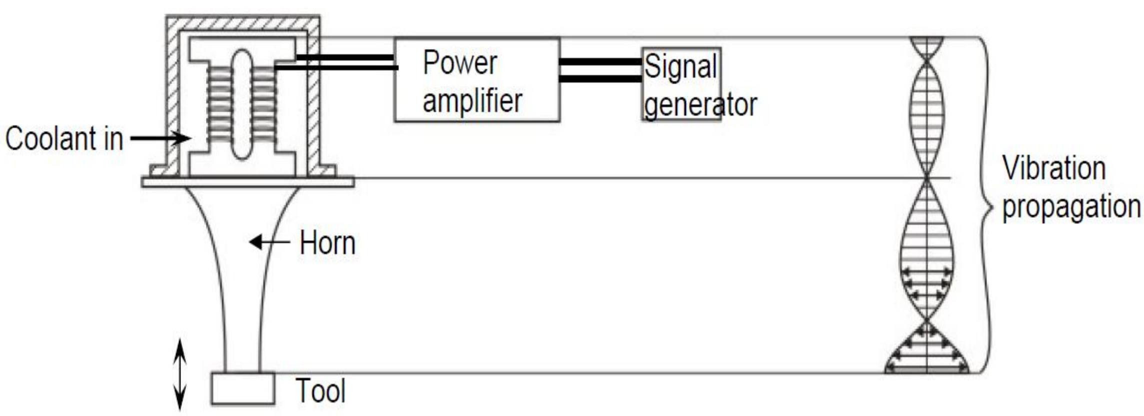

Fig. 1.8. Working of horn as mechanical amplifier of amplitude of vibration [48]

Electrical signal generated is amplified using power amplifier which is then transferred to the transducer. Transducer consists of coils. As signal is supplied to transducer magnetization and demagnetization of coil take place due to which vibrations are produced. These vibrations are sent to horn. As we are moving from the transducer to horn to tool vibration goes on amplifying

1.7.3 Tool

The tools are made of tough, ductile material. Mild Steel is usually used as tool material. Tools are normally soldered or brazed to tool holder.

1.7.4 Tool Holder

The tool holder transfers the vibrations to the tail end. Tool holder is fastened to concentrator and is made of Monel metal (primarily composed of nickel (up to 67%) and copper with some iron and other trace elements) or stainless steel. The shape of the tool holder is cylindrical or conical. Its function is to increase the tool vibration amplitude and to match the vibrator to the acoustic load.

1.7.5 Horn

The horn or concentrator mechanically amplifies the vibration to the required amplitude of 15 to 50 µm. and transfer the vibration to the tool tip. The horn is made of titanium material. The function of horn is that it concentrates the vibration at the single point

There are three shapes of horn used:-

1) Exponential
2) Tapered or conical
3) Stepped

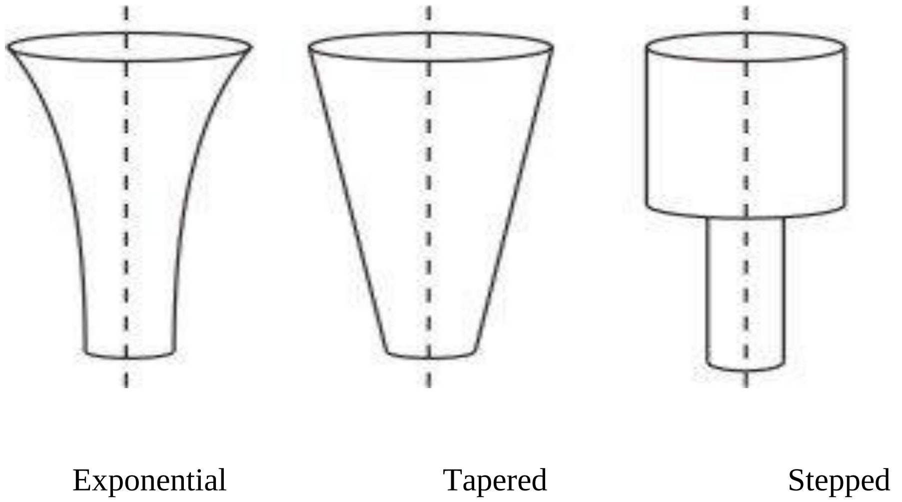

Fig 1.9. Shapes of Horn [48]

1.7.6 Abrasives

The different types of abrasives used in USM are diamond, cubic boron nitride CBN, boron carbide, silicon carbide and aluminum oxide. Boron carbide is most widely used abrasive in USM process. The size of abrasive affects the surface finish. Smaller grit size produces finer finish but reduces machining rate. The rule used in selecting a grit size is that the grit size should be equal to the amplitude of vibration.

1.7.7 Slurry Concentration

Slurry is the mixture of abrasive and water. The slurry is fed in the machining zone i.e. between tool and work piece. The slurry concentration is between 20-60%. MRR is maximum when the slurry concentration is 30%. Slurry Concentration can be changed by changing coolant and by using different sizes of abrasive.

1.7.8 Workpiece

USM is used to machine hard and brittle material such as glass, quartz, ceramics etc. In general, USM is not recommended on the work materials which are softer than Rockwell Hardness Number HRC 40.

1.8 Advantages of USM Process

1. It can be used to machine hard and brittle materials which are difficult to machine otherwise by any type of machining process.

Fig. 1.10:- Square cavities, round through holes and crossing beams in a 4-in borosilicate wafer [49].

2. It can easily machine non – conductive materials such as glass, ceramics and semi- precious stones.
3. Micro ultrasonic machining exhibits good surface finish and dimensional accuracy.
4. Unlike all other non- traditional machining process, ultrasonic machining (USM) does not damage the work piece thermally.

Fig.1.11:- A UM-machined square hole in 0.0175-in. thick glass [49]

Fig. 1.12:- Honeycomb structure machined on the back of a silicon mirror [49]

1.9 LIMITATIONS OF USM PROCESS

1. Ultrasonic machining has relatively low MRR. It is generally less than 50 mm^3/min.
2. There is a restriction on machining area and depth of cut.
3. High rate of tool wear.

1.10 APPLICATIONS OF USM PROCESS

1. It is used for machining very precise and complex shaped articles.
2. It is used to machine hard materials like stainless steel, glass, ceramics, carbide, quartz and semiconductors.
3. This process can be used in conjunction with other new technological process to achieve better efficiency.
4. It is particularly useful in micro drilling hole equal to 0.1 mm.

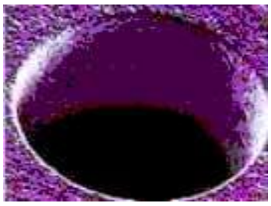

Fig. 1.13:- SEM of a 0.64mm hole ultrasonically machined in an alumi substrate [49]

5. Coining operations of materials like glass, ceramic arts etc.

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Fig 1.14:- Coin with grooving carried out with USM [49]

1.11 COMPARISON BETWEEN NON TRADITIONAL PROCESSES

Table 1.2 Comparisons between Non Traditional Processes

Process / Parameter	USM	AJM	ECM	EDM	EBM	LBM	PAM
Type of Energy	Mechanical	Mechanical	Electrochemical	Chemical	Chemical	Thermal	Thermal
Medium	Abrasive in water	Abrasive in gas	Electrolyte	Dielectric fluid	Vaccum	Normal atmosphere	Argon or Hydrogen
Tool	Soft Steel	Nozzle (WC, Sapphire)	Cu, brass, steel	Cu, brass, Cu-W alloy, Ag-W alloy , graphite	Beam of high velocity electrons	High Power Laser beam	Plasma jet
MRR/TWR	1.5 for WC, 100 for glass work piece	-	Infinity	0.1-10	-	-	-
Maximum MRR (mm^3/min)	-	-	15 *10^3	5* 10^3	10	5	150000
Gap(mm)	0.025-0.04	0.75	0.05-0.3	0.01-0.125	100	150	7.5
Energy Source	Hydraulic Pressure	Pneumatic pressure	High electric Current	Electric spark	High velocity electrons	Powerful radiation	Ionized material
Mechanism of material removal	Brittle fracture caused by impact of abrasive grains due to tool vibrating at high frequency	Brittle fracture by impinging abrasive grains at high speed	Electrolysis	Melting and Evaporation aided by cavitation	Melting , vaporization	Melting , vaporization	Melting
Critical parameters	Frequency, amplitude, tool material, grit size, abrasive material, feed force, slurry concentration , slurry viscosity	Abrasive flow rate and velocity of abrasive jet , nozzle tip distance from work surface, abrasive grain size and inclination of jet	Voltage , current , feed rate , electrolyte, electrolyte conductivity	Voltage, capacitance , spark gap, dielectric circulation, melting temperature	Accelerating voltage, beam current , beam diameter, work speed , melting temperature	Beam power intensity , beam diameter , melting temperature	Voltage , current , electrode gap, gas flow rate, Nozzle dimensions , melting temperature
Material Application	Metals and alloys (particularly hard and brittle work material), semiconductors , non metals e.g. glass and ceramics	Hard and brittle metals, alloys and non metallic materials(e.g. germanium, silicon , glass, ceramics and mica)	All conducting metals and alloys	All conducting metals and alloys	All materials	All materials	All conducting materials
Shape application	Round and irregular holes, impressions	Drilling ,cutting, deburring, etching,	Blind complex cavities, curved surfaces, through cutting	Blind complex holes , micro holes	Drilling fine holes , cutting contours in	Drilling fine holes	Cutting plates

		cleaning	, large through cavities	for nozzles, through cutting of holes which are not circular, narrow slots	sheets, cutting narrow slots		

1.12 RESEARCH MOTIVATION

In recent years there has been problem in comparing and analyzing structures of different type of ultrasonic machining system available in global market. This problem has been solved with the help of graph theoretic approach. Permanent function is used to represent each subsystem of ultrasonic machining system and numerical value thus assigned to various ultrasonic machining system variables thus helps in analyzing total ultrasonic machining system. This methodology is very useful for the designer, researcher as they can generate number of alternative USM design and selection can be made among them. There is also problem in selecting the best ultrasonic machining system from the alternatives available in the market. This problem has been solved with the help of MADM technique i.e. TOPSIS and Graphical Methods. Identification of attribute is useful for defining ultrasonic machining system which is useful for designer, user, and researcher in their respective fields. Different ultrasonic machining system has been represented graphically w.r.t their specification for better understanding and final selection is made on the basis of factors like economic consideration, availability etc.

CHAPTER 2

LITERATURE REVIEW

2.1 General Literature Review about USM

Yu et al.[1] proposed debris accumulation as the main reason leading to low machining efficiency. They observed that the machining speed decreases with increase of the average static load beyond a certain value and considered particle size as the main factor that influence surface roughness. The debris accumulation in the working area leads to a part of static load consumed in impacting the debris instead of removing the material from the work piece resulting in lower machining efficiency but tool rotation helps in removal of debris thereby increasing machining speed.

Kai et al.[2] performed micro ultrasonic machining on soda-lime glass using tungsten carbide abrasive 0.6 μm in grain size with oscillate amplitudes of 0.4-1.6μm, a machining load of 0.025-0.2N and oscillation frequency of 40kHz. It was found that drilling speed increases with increase in machining load in case of single tools using cemented carbide tool. It also concluded that machining load or oscillation amplitude has no influence on tool wear ratio. They also concluded that w.r.t 0 tool wear ratio , PCD tools has more excellent resistance than cemented carbide tools.

Yu et al.[3] identified low cycle fatigue as the main factor causing tool wear in micro USM. They proposed a theoretical model to estimate tool wear. They concluded that tool rotation has no influence on tool wear. They compared experimental results of tungsten and stainless steel with 316L with theoretical values. It was found that large errors are generated in case of small diameter tools and large sized particle.

Zeng et al.[4] discussed the result of tool wear and cutting forces in RUM of SiC. They concluded that tool wear on end face is much more than on lateral face and maximum cutting force increases with number of holes drilled during first tool wear stage and starts decreasing during a second tool wear stage. They also concluded that the tool wear in RUM of SiC has two stages. In the first stage, attritious wear dominates whereas in the next stage, bond fracture dominates.

Zarepour and Yeo [5] developed a model to predict material removal modes in ductile and brittle material when the brittle material is impacted by single sharp abrasive particle in micro ultrasonic machining process. They predicted the material removal modes for silicon <100> and fused quartz. They studied morphology of the crater formed and observed three modes of material removal namely pure ductile, partially ductile (transition mode) and pure brittle.

Zarepour et al.[6] developed a micro- USM system w.r.t measurement and monitoring of static force as well as tooling and work piece clamping. They concluded that the minimum and maximum variation in amplitude w.r.t position across the work piece is 5.2% and 8% respectively. They also concluded that the ultrasonic vibrations can be transmitted to the work piece effectively by the vaccum chuck.

Li et al.[7] developed a three- dimensional finite element analysis (FEA) model to study the effects of three parameters (cutting depth , support length and pretightening load) on the maximum normal stress and von Misses stress in the region where the edge chip initiates. They resulted that as the support length increases, the edge-chipping thickness decreases. They concluded that the maximum values of the maximum normal stress and the von Misses stress increases as the cutting depth increases. They also concluded that the maximum values of the maximum normal stress and the von Mises stress decreases slightly as the support length increases before reaching the critical length and the maximum values of the maximum normal stress and the von Mises stress decreases as the support length exceeds the critical length.

Shen et al.[8] investigated the effects of assisted ultrasonic vibration in the operation of micro end milling. They investigated cutting force, chip formation, surface topography , surface roughness , and dimensional accuracy. They showed that the ultrasonic vibration causes the significant change in the profile of cutting force. They observed that the average value of cutting force decreases slowly with the increase of vibration amplitude. It was observed that larger amplitude produces smaller chips. They observed and compared the topographies of machined surfaces, it was found that ultrasonic vibration assisted milling can reduce defects and obtain more uniform machined surfaces. They concluded that the ultrasonic vibration in the feed direction has negative effect on the roughness of machined slot bottom surface, but has positive effect on the dimensional accuracy of slot width.

Peng et al.[9] investigated the chip generating characterstics in grinding of brittle materials with vertical elliptic vibration assistance. They discussed the effect of elliptical vibration on the measured surface roughness Ra. They observed that the surface roughness Ra decreases with the assistance of elliptical vibration and improves as the welding speed increases. They concluded that the surface roughness Ra decreases and surface improves when the elliptic vibration induced between the grains and work-piece eliminates the crests on the machined surface. They also concluded fully developed and appearance of a chip produced as a completely continuous form by ductile mode cutting because of the compound effects in ultrasonically assisted method.

Liu et al.[10] developed a cutting force model for rotary ultrasonic machining (RUM) of brittle materials. They predicted influences of input variables on cutting force and determined trends experimentally. (1) cutting force increase as abrasive concentration and feed rate increase and (2) cutting force decreases as abrasive size, vibration amplitude, and spindle speed increases.

Aurich et al.[11] described the design and manufacture of single-edge micro end-mills with diameters between 10 and 50 mm and a variable helix angle. They also described the use of these end-mills in titanium and polymethyl methacrylate (PMMA). They showed grinding as process suitable for the manufacture of ultra-small micro end mills.

Guo et al. [12] developed a vibration-assisted polishing machine using a magnetostrictive vibrating polisher to improve the efficiency, surface roughness and constancy of finishing. They kept the polishing force steady in the polishing force control system and improves the stability of ultra-precision finishing.

Heisel et al. [13] investigated drilling of stone materials, i.e. different granites and marble on which USM is applied. They resulted that the drilling torque decreases with 20% increase of amplitude of original value.

Nategh et al.[14] studied the kinematics of the relative motion between the cutting tool and the work-piece. They predicted that the width of pressed regions increases when the cutting speed decreases or the vibration amplitude increases. They resulted the increase of the depth of pressed regions due to increase in the feed rate lead to increased hardness of the lateral surface. They found that , the ratio of the cutting duration to the cycle time would decrease by reducing the cutting speed or by increasing the vibration amplitude indicating the effectiveness of ultrasonic vibration at lower cutting speeds and larger vibration amplitudes.

Zarepour and Yeo [15] developed an the approach of single abrasive particle impingement in micro ultrasonic machining with the purpose of providing insights into material removal modes. They resulted an improvement in surface integrity of the machined micro features as well as material removal rate in micro USM process.

Aziz et al.[16] focused on the efforts for minimization of burr formation and improvement in roughness of hole surface in micro through-hole machining. They focused on the effect of drill point angle and ultrasonic vibration to the hole entrance and exit burrs formation during micro hole machining. They considered tool with a drill point angle of 118° as the best geometry of the drill because of formation of burrs in smaller size.

Muhammad et al.[17] investigated the effect of vibration on cutting forces and temperature levels in a cutting region for various cutting conditions. They concluded that the cutting force increases with the increase in depth of cut. They also concluded an increase of Temperature in the cutting region increases due to increase in the depth ofcut and cutting speed, both in CT and UAT.

Nik et al.[18] studied the effect of imposition of ultrasonic vibration on the grinding of Ti6Al4V alloy. They studied Comparison between CG and UAG at several cutting and feed speeds and cutting depths and the effect of ultrasonic vibration in dry condition. They concluded the selection of higher depth of cut and feed with better surface in UAG as compared to CG.

Bertsche et al.[19] determined the relationships between input parameter, cutting parameter, and process output parameter for rotary ultrasonic milling. They defined macro kinematics between the tool and material for RUSM; defined the path of diamond tool's path in relation to the work piece and the trajectories of single abrasive grains were reproduced by describing the kinematics of the effective position, velocity, and acceleration vectors of a single abrasive grain.

Jatinder Kumar and Vinod Kumar [20] focused on parametric optimization of ultrasonic machining of pure titanium metal with TWR as response, and validation of the optimized value of TWR experimentally. They concluded tool material as an important factor followed by power rating of USM equipments. They concluded that type of abrasive and grit size significantly influence TWR.

Vinod Kumar and Jatinder Kumar[21] predicted the mechanical stresses and strains produced with the tool during the ultrasonic machining process by using finite element approach .They studied the behavior of abrasive slurry coming out of nozzle by using ANSYS CFX software.

Wang et al.[22] discussed fundamental principles of ultrasonic machining, the material removal mechanism and important factors are calculated. They concluded that the average cutting forces in ultrasonic vibration cutting are smaller than those in conventional cutting. They also concluded that Decrease in the cutting speed of the work-piece and/or increase in the vibration frequency will result in better surface quality.

Kang et al.[23] investigated the material removal rate and surface quality of the alumina (Al_2O_3) which was ultrasonically machined using SiC abrasive under various machining conditions. They resulted that material removal rate increases as the static pressure and slurry concentration increases. They concluded higher material removal rate in case of rectangular sectional profile of the tool as compared to square sectional profile of the tool when tool of same cross-section area are used. They resulted an improved surface roughness of about 0.76 μm when machining was done by using abrasive of mesh number 600.

Choi et al.[24] studied the chemical-assisted ultrasonic machining (CUSM) method in order to improve the material removal rate and the integrity of the machined surface. They developed the chemical effect by using a low concentration HF solution in the chemical-assisted ultrasonic machining process in order to overcome low material removal rate and surface quality.

Churi et al. [25] studied the effects of machining variables in Rotary ultrasonic machining of titanium alloy. They concluded that cutting force and surface Roughness decreases as spindle speed increases. They also concluded that cutting force ,MRR and surface roughness increases as the feed rate increases. It was concluded that cutting force decreases initially and then increases as ultrasonic power increases and surface roughness decreases as the ultrasonic power increases.

Curodeau et al. [26] proposed a new m-machining process, namely the ultrasonic abrasive m-machining process (UAmM) by using thermoplastic tooling material. They investigated Two different m-machining modes sthat is application of the hammering mode for µmachining and application non-contact ultrasonic machining mode for µ polishing.

Chandra Nath and M. Rahman et al.[27] studied the effect of three important parameters: tool vibration frequency, tool vibration amplitude and work-piece cutting speed on ultrasonic vibration cutting (UVC). They concluded UVC method as a suitable technique to achieve high-quality finish surfaces for Inconel 718. They concluded that a minimum Ra value of 0.6 mm and 2.4 mm was achieved with the UVC method CT method respectively. They also concluded that value of TWCR should be kept as low as possible that is by increasing both the tool vibration frequency and amplitude, as well as by decreasing the work-piece cutting speed.

Vinod Yadava and Aniruddha Deoghare [28] developed finite element method (FEM) for the design of a horn for rotary ultrasonic machining (RUM). They developed a mathematical model for the determination of displacement within the horn used in rotary ultrasonic machining (RUM). They concluded that the amplification factor is more for rotary USM over conventional USM in case of no horn rotation. They also concluded that the stresses at the bottom surface of the horn are approximately equal to zero and the stresses obtained for the resonance frequency is much less than that obtained for the other frequencies.

Rupinder Singh and J. S. Khamba [29] studied the effect of six input parameters that is tool matter, power rating, slurry type, slurry heat, slurry concentration, and slurry grit size on the tool wear rate in the ultrasonic machining of titanium and its alloys. They developed a mathematical model for tool wear rate; using Buckingham's π-theorem for stationary ultrasonic machining of titanium and its alloys. They developed the model by considering the interactions among input parameters.

Mathieson et al.[30] studied the characterisation of the nonlinear behaviour of two power ultrasonic devices designed for rock drilling. They developed vibration testing method to reduce the thermal effects on the measured responses.

Haw et al.[31] studied the surface integrity of the USMed surface and developed a way to minimize the scattered cracks so that good surface finish could be achieved. They developed a multistage micro-USM process and achieved the value of surface roughness better than 0.2 μm. They observed a rough surface with scattered chippings and deep penetrated cracks when large grit size abrasives and/or fast feed rate were used. They concluded that slower the feed rate the better will be surface roughness and shallower the sub-surface cracks under the same oscillation amplitude/frequency and the same abrasives .

Jianxin and Taichiu [32] studied the effect of workpiece material properties and microstructure on the MRR in ultrasonic machining of alumina based ceramic composite and concluded that MRR and surface roughness decreases as the fracture toughness increases.

Rao et al. [33] presented the optimization of USM process parameters using three non traditional algorithms artificial bee colony (ABC), harmony search (HS), and particle swarm optimization (PSO). They compared the results obtained by three above algorithms with that obtained by using genetic algorithms (GA) .They concluded that the ABC, HS, and PSO algorithms outperformed GA, showing a considerable improvement over GA.

Baek et al. [34] proposed a new method to achieve a high precision USM by using the coating on the work piece. This method provided good surface quality by using USM with brittle materials.

Chakravorty et al. [35] presented four relatively simple methods i.e. WSN, GRA, MRSN,UT for the optimization of the multiple responses of the USM process and compared the overall optimization performances of these four methods. They concluded that WSN or UT method gives the better overall optimization performances of USM process and WSN method is preferable to UT method as it provides less complexity.

Singh and Khamba [36] investigated the ultrasonic machining of tough materials like titanium and its alloy and studied the effect of power rating on work hardening of work piece and tool. They concluded that MRR and TWR decreases as the grit size of abrasive slurry increases and better surface finish is attained with increase in grit size as fine abrasive grain particle comes in to picture with increase in grit size.

Singh and Khamba [37] reviewed machining of titanium and its alloy with different slurry i.e. silicon carbide, boron carbide and alumina. They obtained best results by the use of SS tool and boron carbide slurry. They concluded that on average there was 34.46% improvement in MRR for the work piece like TITAN15 and TITAN31.

2.2 Literature Review Based on the methodology

2.2.1 Literature Review based on MADM Approach

Bhangale et al. [38] proposed a methodology i.e. MADM approach TOPSIS to evaluate , rank and select robot from large number of robot for particular application using elimination search based on critical selection attribute. They concluded that the methodology was suitable for generating database of robots available in the market and their subsequent retrieval. This database will help the manufacturers , designers and users related to robot area for improving the overall productivity of the organization. Evaluation and ranking of the robot has been done mathematically i.e. TOPSIS and graphically.

Agrawal et al. [39] presented a methodology i.e. TOPSIS to evaluate and select an optimum gripper at the time of changing over from one job to another in a fully automated industry or when grippers and robots are to be purchased from global market. They developed comprehensive classification and coding scheme for grippers. The method is suitable to flexible manufacturing system where robot itself can select optimum gripper for changing over to new job. The classification and coding scheme for grippers was suitable for the development of a large database of available grippers and their subsequent retrieval. It was hoped that method will help the users to scan the properties of a large number of grippers and then select the best one in the shortest possible time and final choice may be made on the basis of the availability of the gripper,economic considerations,management constraints and international market policies etc.

Kiran et al.[40] proposed a methodology i.e. MADM for evaluation and selection of mechatronic system by identifying list of attributes that influence structure and performance of mechatronic system and then by an attribute based coding scheme identification and differentiation of mechatronic system was developed. They identified 3-stage selection procedure which includes elimination search, TOPSIS based evaluation and ranking and other graphical methods (line graph and spider diagram). Ranking of mechatronic system alternatives was done based on the Euclidean distance of alternatives from the hypothetically worst and hypothetically worst mechatronic systems. This methodology ensures that the selected mechatronic system is closest to hypothetically best mechatronic system and farthest from hypothetically worst mechatronic system.

Garg et al.[41] proposed methodology i.e. MADM for evaluation , comparison ,ranking and optimum selection of power plants. This methodology was found useful for computer processing. The computer software was developed for elimination search and TOPSIS approach is user friendlyand does not require technical knowledge of the plant attribute for its use.

Kumar and Agrawal [42] proposed a methodology i.e. MADM for the optimum selection of electroplating system. The n-digit alpha numeric code was developed through an illustrative example of electroplating system for better understanding of different electroplating elements. The method gives the relative importance of one attribute to another attribute. The 3-stage selection procedure was identified. This methodology ensures that the selected electroplating system is closest to positive benchmark solution and is farthest from negative benchmark solution. Evaluation and ranking of electroplating system was done both mathematically and graphically.

2.2.2Literature Review based on Graph Theoretic Approach

Singh and Agrawal [43] proposed methodology i.e. Graph Theoretic Approach for the modelling and integerating manufacturing system analysis to find out the optimized solution. Elements constituting manufacturing system and interaction between them was represented by graph theory model. The permanent function was used to study subsystems of different manufacturing system. The numerical value based index may be used as tool in comparing , ranking and selecting appropriate manufacturing system from the alternatives available in the global market. The coefficient of similarity and dissimilarity was used to compare different structures of manufacturing system.

Garg et al. [44] developed a deterministic quantitative model based on graph theoretical methodology for comparing various technical and economical features of wind, hydro and thermal power plants and also used to evaluate and rank the power plants in ascending or descending order in accordance with the value of their suitability index. They concluded that this methodology allows a decision maker to perform , not just general analysis but also other focused analysis regarding his personnel preference.

Prabhakaran and Agrawal [45] proposed a graph theory and matrix algebra to develop an integrated systems model for the structure of composite product system in terms of its constituents and interaction between constituents and molding processes. This proposed methodology considered all the attributes responsible for design, production and process parameters for developing a composite product. The composite product is first modelled with the help of graph theory, then by variable adjacency matrix ,and then bypermanent function. The permanent function has provided an opportunity to carry out structural analysis of composite product interms of strength ,weakness, improvement and optimization by correlating the properties of a composite with its structure.

2.3 Research Issues

The research issues identified from literature has been summarized in Table 2.1

Table 2.1: Research Issues

Author Name	Paper Name	Broad Area of Classification	Conclusion
Yu et al. [1]	Influence of debris accumulation on material removal and surface roughness in micro ultrasonic machining of silicon	Influence of machining parameter on machining performance	1.Machining speed decreases with the increase of average static load beyond a certain value 2.Tool rotation increases machining speed by removing debris.
Kai et al. [2]	Micro ultrasonic Machining Using Multitools	Micro ultrasonic machining on soda-lime glass using tungsten carbide abrasive 0.6 μm in grain size with oscillation amplitudes of 0.4-1.6μm, machining load of 0.025-0.2N and oscillation frequency of 40kHz.	1.Drilling speed increases with increase in machining load in case of single tools using cemented carbide tool 2.w.r.t 0 tool wear ratio , PCD tools have more excellent resistance than cemented carbide tools.
Yu et al. [3]	Prediction of tool wear in micro USM	Proposed theoretical model to predict tool wear.	1.Low cycle fatigue , important factor causing tool wear in micro USM
Zeng et al. [4]	Experimental observation of tool wear in RUM of advanced ceramics	Experimental observation on tool wear in RUM of SiC.	1.Tool wear on the end face is much more than that on lateral face.
Zarepour and Yeo [5]	Predictive modelling on material removal modes in micro ultrasonic machining	Prediction of Ductile and brittle material removal modes when a single sharp abrasive particle impact on brittle material in micro ultrasonic machining process.	1. A new model was developed in micro-USM to predict material removal mode quantitatively based on the properties of the workpiece and particles as well as ultrasonic characteristics of the system 2. The morphology of the craters formed by particle impacts was studied and three modes of material removal were observed; namely, pure ductile, partially ductile (transition mode) and pure brittle.

Author Name	Paper Name	Broad Area of Classification	Conclusion
Zarepour et al. [6]	A new approach for force measurement and work piece clamping in micro-ultrasonic machining	A micro –USM system was developed w.r.t measurement and monitoring of static force as well as clamping of tool and workpiece	1.The vaccum clamping system was used for holding the work piece firmly onto ultrasonic vibrating horn during the machining time
Li et al. [7]	Edge –chipping reduction in RUM of ceramics.	Study of Effects of three parameters(cutting depth, support length and pretightening load) on the maximum normal stress and Von Mises stress in the region where edge chipping initiates with the help of finite element analysis(FEA) model.	1.Maximum normal stress and von Mises stress increases as the cutting depth increases. 2.No effect of pretightening load on maximum normal stress and von Mises stress. 3Maximum normal stress and von Mises stress decreases slightly when support length increases but is below critical value 4.Sharp decrease in the maximum value of maximum normal stress and von Mises stress , when the support length exceeds the critical value.
Shen et al. [8]	Ultrasonic vibration assisted milling of aluminium alloy	Effects of assisted ultrasonic vibration aare investigated in the operation of micro end milling	1. Negative effect of Assisted Ultrasonic vibration on the surface roughness of machined bottom slot. 2. Positive effect of Assisted Ultrasonic vibration on the dimensional accuracy of slot width.
Peng et al. [9]	Characterstics of chip generation by vertical elliptic ultrasonic vibration- assisted grinding of brittle materials	Characterstics of generating chip was investigated in grinding of brittle material with vertical elliptic vibration assistance.	The surface roughness Ra decreases and surface improves when the elliptic vibration induced between the grains and work piece eliminates crests on the machined surface.
Liu et al. [10]	A cutting force model for RUM of brittle materials.	A cutting force model for RUM of brittle materials was developed to predict the influence of input variables on cutting force.	1.Cutting force increases as abrasive concentration and feed rate increases. 2. Cutting speed decreases as abrasive size, vibration amplitude and spindle speed increases.
Aurich et al. [11]	Manufacture and application of ultra-small micro end mills.	Described the design and manufacture of single – edge micro end –mills with diameter between 10 and 50 µm and variable helix angle	Positive influence of helix angle on the ductile behaviour of Ti-6Al-7Nb.

Author Name	**Paper Name**	**Broad Area of Classification**	**Conclusion**
Guo et al. [12]	Ultra – precesion finishing of micro-aspheric mold using a magnetostrictive vibrating polisher.	A vibration assisted polishing machine using magnetostrictive vibrating polisher was developed to improve the efficiency, surface roughness and stability of finishing	Polishing force is kept constant in polishing force control system and improves the stability of ultra-precision finishing
Heisel et al. [13]	Ultrasonic –assisted machining of stone	In ultrasonic assisted machining , drilling of stone materials i.e. different granites and mables was investigated.	Resultant forces and torque reduced upto 20% of the initial value when ultrasound is applied.
Nategh et al. [14]	Analytical modeling and experimental investigation of ultrasonic vibration assisted oblique turning : Kinematic analysis	Kinematics of the relative motion between the cutting tool and work piece	Increase in the width of the pressed region due to decrease in cutting speed or increase in vibration amplitude ; also increase in the feed rate leads to increase in depth of pressed region.
Zarepour and Yeo [15]	Impingements of single abrasive particle to determine material removal modes in micro ultrasonic machining	Methodology was established on the Impingement of single abrasive particle to determine ductile and brittle removal modes in micro ultrasonic machining	1.Ductile material removal mode was achieved when single abrasive particle of size 0.37µm was impinged at vibration amplitude of 3µm. 2. Brittle material removal mode was achieved when single abrasive particle of size 0.37µm was impinged at vibration amplitude of 4µm.
Aziz et al. [16]	Micro hole machining with minimum burr formation by the use of micro compound tool	Effect of drill point angle and ultrasonic vibration applied to the hole entrance and exit burrs formation during micro hole machining.	1 Tool with drill point angle of 118° is considered as the best geometry of the tool because it forms smaller size burr 2 Tool with drill point angle of 100° forms large exit burr 3 Tool with drill point angle of 130° shows a good performance in initial 200 holes and get worse at the tool wear goes on.
Muhammad et al. [17]	Numerical Modelling of Vibration-Assisted Turning of Ti-15333	The effect of vibration on cutting forces and temperature levels in a cutting region for various cutting conditions were investigated by the use of three dimensional finite element model for both conventional	1.During simulation it was observed that the reduction in the cutting force was 69% whereas during actual experiment it was observed that the reduction in cutting force increased from 69% to 77%. 2. Temperature in the cutting region in UAT at maximum penetration is higher when compared to CT. 3. The average temperature of

		and ultrasonically assisted turning techniques	the cutting tool in UAT is lower when compared to CT. 4. Temperature in the cutting region increases as the depth of cut and cutting speed increase, both in CT and UAT.
Nik et al. [18]	Ultrasonic-Assisted Grinding of Ti6Al4V Alloy	The effect of imposition of ultrasonic vibration on the grinding of Ti6Al4V alloy was studied.	1.In UAG there is average reduction in 13.5% and 14.2% of normal and tangential force respectively. 2.There is average improvement of 10% in surface roughness when ultrasonic vibration is imposed.
Bertsche et al. [19]	An analytical model of rotary ultrasonic milling	The effect of individual input parameter on cutting parameter was studied in RUSM.	1. The penetration angle for RUSM will be approximately equal to that of ultrasonic drilling and it increases as the ultrasonic amplitude or frequency increases
Jatinder Kumar and Vinod Kumar [20]	Evaluating the Tool Wear Rate in Ultrasonic Machining of Titanium using Design of Experiments Approach	Parametric optimization of ultrasonic machining of pure titanium metal with TWR as response, and validation of the optimized value of TWR experimentally	1. Abrasive type and grit size have significant effect on TWR. 2. the optimal value of TWR was established as 0.45 mg/min , as experimentally verified.
Vinod Kumar, Jatinder Kumar [21]	Prediction of tool and nozzle flow behaviour in ultrasonic machining process	A model was developed using finite element approach to predict the mechanical stresses sand strains produced in the tool during ultrasonic machining process	1.The efficiency of the nozzle will be maximum when the nozzle is placed at the distance of around 10 mm from the cutting zone. 2.The velocity of fluid at the distance of 1mm from the outlet was found to be 20.624m/sec
Wang et al. [22]	Theoretical and experimental studies of ultra precision machining of brittle materials with ultrasonic vibration	Fundamental Principles of ultrasonic machining, the material removal mechanism and the calculation of critical factors are studied	1. The average cutting forces in ultrasonic vibration cutting are smaller than those in conventional cutting. 2.Surface quality improves as the cutting speed of the work piece decreases and /or vibration frequency increases.
Kang et al. [23]	An experimental study on ultrasonic machining characteristics of Engineering Ceramics	Alumina (Al_2O_3) was ultrasonically machined using SiC abrasive under the applied amplitude of 0. 02 mm, 27kHz frequency , three slurry ratios 1:1,1:3, 1:5 With different tool shapes and under the applied static pressure levels to investigate MRR and	1.MRR was found to be 18.97mm^3/min when mesh number was 240,slurry ratio was 1:1, static pressure was 2.5kg/cm^2. MRR decreases as static pressure increased from 2.5 kg/cm^2 to 3kg/cm^2. 2.MRR decreases as the size of abrasive decreases. 3. Higher MRR in case of rectangular sectional profile of the tool as compared to square sectional profile of the tool when

		Surface quality of the machined samples	tool of same cross –sectional areas are used. 4. improved surface roughness was found to be 0.76μm Ra when machining was done with the abrasive of mesh number 600.
Choi et al. [24]	Chemically –assisted ultrasonic machining of glass	Chemically –assisted ultrasonic machining (CUSM) method was introduced in order to improve MRR and integrity of machined surface.	1.Surface roughness improved up to 40% at macro drilling. 2.MRR was improved up to 200% at micro drilling. 3.Chemically assisted ultrasonic machining uses low concentration i.e. under 5% HF solution to have chemical effect.
Churi et al. [25]	Effects of machining variables in RUSM of titanium alloy.	Experimental study on the RUSM of titanium alloy.	1.Cutting force and surface roughness decreases as spindle speed increases. 2. Cutting force, MRR and surface roughness increases as the feed rate increases. 3. Cutting force decreases initially and then increases as the ultrasonic power increases. 4. Surface roughness decreases as the ultrasonic power increases.
Curodeau et al. [26]	Ultrasonic abrasive μ machining with thermoplastic tooling	Viscoelastic thermoplastic composite material is used as tooling to conduct ultrasonic μ machining operations.	1. A 22-mm uniform surface layer was removed from a P20 32HRC hardness sample. Three material removal mechanisms were observed: simple indentation enforced by perpendicular motion of the tool, abrasive particle rolling along a tangential direction and sliding or micro cutting mechanisms along multiple tangential directions.
Chandra Nath and M. Rahman [27]	Effect of machining parameters in ultrasonic vibration cutting	Mechanism how the tool vibration frequency , tool vibration amplitude and work piece cutting speed effect UVC.	1.A minimum Ra value of 0.6 mm was achieved with the UVC method whereas 2.4 mm was achieved with the CT method for the same cutting condition. 2.In order to achieve high quality surface finish for Inconel 718 ,UVC method is found to be the best method.
Vinod Yadava and Aniruddha Deoghare [28]	Design of horn for rotary ultrasonic machining using the finite element method	Developed finite element method (FEM) for the design of horn for rotary ultrasonic machining	1. The amplification factor is more for rotary USM over Conventional USM without horn rotation for the same material properties and the boundary conditions. 2. The stresses at the bottom surface of the horn are nearly Zero because the horn is free to move at that end.

Rupinder Singh and J. S. Khamba [29]	Mathematical modelling of tool wear rate in ultrasonic machining of titanium	1.A mathematical model was developed for the tool wear rate by the use of Taguchi model ; using Buckingham's π-theorem for stationary ultrasonic machining of titanium and its alloys. 2.Effect of Six input parameters, namely, tool material, power rating, slurry type, slurry temperature, slurry concentration, and slurry grit size on tool wear rate in ultrasonic machining of titanium and its alloys	Ultrasonic power rating at 90% that is at 450 W, with S.S tool and 500-grit-size slurry gave best results for TWR when titanium and its alloys are machined with USM
Matheson et al.[30]	Characterisation of nonlinear behaviour of power ultrasonic drilling horns	Characterisation of the nonlinear behaviour of two power ultrasonic devices designed for rock drilling	Developed vibration testing method to reduce the thermal effects on the measured response.
Haw et al. [31]	Study on the Surface Integrity of Micro-Ultrasonic Machined Glass-ceramic Material	The surface integrity of the US Med surface was developed to minimize the scattered cracks so as to achieve good surface finish	1. Slower the feed rate the better will be surface roughness and shallower the sub-surface cracks under the same oscillation amplitude/frequency and the same abrasives. 2. Higher the abrasive concentration poorer the surface finish.
Jianxin and Taichiu [32]	Ultrasonic machining of alumina-based ceramic composite	The effect of work material properties and microstructure on MRR was studied in the Ultrasonic machining of alumina-based ceramic composite	MRR and surface roughness decreases as the fracture toughness increases.
Rao et al. [33]	Parameter Optimization of Ultrasonic Machining Process using Nontraditional Optimization Algorithms	1 Optimization of USM process parameter were presented using three non traditional algorithms i.e. ABC,HSand PSO 2 Comparison of result obtained by three non traditional algorithms i.e. ABC,	ABC,HS and PSO showed the considerable improvement over GA

		HS and PSO with that obtained by using GA	
Baek et al. [34]	Enhancement of surface quality in ultrasonic machining of glass using a sacrificing coating	A new method was proposed to achieve a high precision USM by using coating on work piece	A new method showed good surface quality by using USM with brittle materials
Chakravorty et al. [35]	Optimization of Multiple responses of Ultrasonic Machining (USM) process : A Comparative study	Four methods i.e. WSN, GRA, MRSN,UT were presented for the optimization of the multiple responses of the USM process	WSN or UT method gave better overall optimization performances of the USM process
Singh and Khamba [36]	Investigation of ultrasonic machining of titanium and its alloys.	The effect of Power rating on work hardening of work piece and tool was studied	1 MRR and TWR decreases as the grit size of abrasive slurry increases 2 Better surface finish is attained with increase in grit size
Singh and Khamba[37]	Comparison of slurry effect on machining characterstics of titanium in ultrasonic drilling	The machining of titanium and its alloys with different slurry i.e. silicon carbide , boron carbide and alumina	Boron carbide and stainless steel tool was found to give the best MRR

Author Name	Paper Name	Broad area of Classification	Usefulness of methodology
Bhangale et al. [38]	Attribute based specification, comparison and selection of a robot	MADM approach TOPSIS was used to evaluate, rank and select robot from large number of robot available in global market for particular application using elimination search	Methodology was suitable to generate database of robot available in the market and their retrieval and this database improved the overall productivity of the organization with the help of manufacturers , designers and user of robot area.
Agrawal et al. [39]	Computer-aided evaluation and selection of optimum grippers	TOPSIS was used to evaluate and select an optimum gripper at the time of shifting over from one job to another in fully automated industry	The method is suitable to flexible manufacturing system where robot itself can select optimum gripper for changing over to new job. It was hoped that method will help the users to scan the properties of a large number of grippers and then select the best one in the shortest possible time and final choice may be made on the basis of the availability of the gripper,economic considerations, management constraints and international market policies etc.
Kiran et al. [40]	Coding, evaluation and optimal selection of a mechatronic system	MADM methodology was used for the evaluation and selection of a mechatronic system	1)This methodology was useful in selection of a mechatronic system and useful for customer in selection of best mechatronic product from the alternatives of mechatronic system available in the market on the basis of value of pertinent attributes specified. 2) Many alternatives of mechatronic system can be generated just by changing the values of attribute in a specified range.
Garg et al. [41]	Coding, evaluation and selection of thermal power plants – A MADM approach	MADM was used for evaluation , comparison, ranking and optimum selection of power plants	MADM was found useful for short listing of potentially suitable plant and for solving non square matrix This methodology was found suitable for computer processing The computer software was developed for elimination search and TOPSIS approach so user does not require any technical knowledge of the plant attribute for its use.

Kumar and Agrawal[42]	Attribute based specification, comparison and selection of electroplating system using MADM approach	Selection of electroplating product /plant from a large variety of electroplating configuration and manufacturing plant/products	1.The selection procedure will help the user to select the most suited electroplating product for his operational needs. 2.It helps the decision maker(s) to organize the problem to be solved and carry out analysis , comparison and ranking of alternatives. 3.Designers and manufacturers of different subsystems can visualize, design and analyze the requirements of elements and their interactions to respond to the needs of highly competitive and vibrant market 4. Cause and effect analysis based on Fish bone diagram using 100 attribute coding scheme will directly help in improving manufacturing technology.
Singh and Agrawal [43]	Structural modelling and integrative analysis of manufacturing systems using graph theoretic approach	Graph Theoretic model was used for modelling and integrating manufacturing system analysis to find out the optimized solution	1) The numerical values in the permanent function may act as powerful tool in comparing , ranking and selecting an appropriate design from various alternatives available based on performance measures. 2) The coefficient of similarity and dissimilarity may act as another tool for comparison of different structural design of manufacturing system. 3) Using this methodology ,computional analysis can be carried out which will develop a software for selecting the optimum parameter for real time operation of manufacturing system
Garg et al. [44]	Selection of power plants by evaluation and comparison using graph theoretic methodology	A deterministic quantitative model based on graph theoretic methodology was developed to compare the technical and economical features of wind ,hydro and thermal power plants and also used to evaluate and rank the power plants in ascending or	This methodology allows a decision maker to perform , not just general analysis but also other focused analysis regarding his personnel preference

		descending order in accordance with the value of their suitability index	
Prabhakaran and Agrawal [45]	Structural Modeling and Analysis of Composite Product System:A Graph Theoretic Approach	1) With the help of graph theory and matrix algebra an integrated system model for the structure of composite product system was developed in terms of its constituents and interaction between constituents and molding processes 2) The composite product was first modelled with the help of graph theory , then by variable adjacency matrix and then by permanent function.	The permanent function provided an opportunity to carry out structural analysis of composite product in terms of its strength, weakness, improvement and optimization by correlating properties of a composite with its structure

2.4 GAP ANALYSIS

- Very less study has been done on geometry variability of tool
- Very less work has been carried out by the influence of super thin coating on micro milling tool.
- It is desired to investigate particularly on tool wear.
- Very less work has been done on the systematic study of the effects of machining variables on RUSM of titanium and its alloy.
- Very less study has been done on the development of polishing tools for different shapes of micro structured molds.
- Very less study has been carried out on the effects of ultrasonic vibration on micro –milling process in terms of matching parameter and mechanism causing excessive tool wear.
- Very less study has been done to predict the material removal rate based on mode in micro ultrasonic machining process.
- Very less study has been done on the stress analysis of tool and does not find any effect on the mixing of abrasive slurry.
- Graph theoretic approach was not applied on ultrasonic machining system for structural , modeling and analysis of ultrasonic machining system.
- MADM was not applied on ultrasonic machining system for coding , evalution and selection of ultrasonic machining system.

After the consideration of Gap Analysis, Graph Theory and MADM approach is being proposed for modeling ,analysis, evaluation and selection of Ultrasonic Machining System for comparison and ranking of best Ultrasonic Machining System from the alternates available in the market.

CHAPTER 3:-GRAPH THEORETIC APPROACH

3.1 INTRODUCTION

A graph G is represented by [V, E]. Here {V} = (v_1 , v_2 , v_3 , … … … , v_n) represent vertices or nodes and {E} = (e_1 , e_2 , e_3 , … … … … , e_n) represent edge of the graph such that each edge e_k is formed by the pair of vertices. The vertices v_i and $v_j$are said to be adjacent if there is an edge e_{ij}connecting them. The most common representation of a graph is by means of a diagram, in which vertices are represented by small points or circles, and each edge as the line segment joining its end vertices. Fig.3.3 represents a hierarchal tree showing four subsystems as identified that constitute ultrasonic machining (USM) system. In fig 3.5 subsystems are represented by the vertices of the graph and the interaction of the subsystems is represented by the edges of the graph.

If the node 'i' has a relative importance over another node 'j', then directed edge or arrow is drawn from node 'i' to node 'j'

The graph is basically of two types i.e. directed graph and undirected graph.

In mathematics, a **directed graph** or **digraph** is a graph, or set of vertices associated by edges, where the edges have a direction linked with them. In prescribing terms a digraph is a pair $G = (V, A)$ (sometimes$G = (V, E)$) of

- A set V, whose elements are called vertices or nodes,
- A set E of well-organized pairs of vertices, called arcs, fixed edges, or arrows.

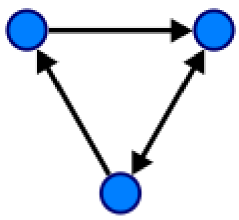


Fig. 3.1 Directed Graphs

An undirected graph is one in which edges have no direction. The edge (a, b) is identical to the edge (b, a), i.e., they are not well-organized pairs. An undirected graph G consists of a set of vertices V and a multi set of edges E unordered pairs of vertices. We usually write G = (V, E) is called undirected graph. Maximum no. of edges in an undirected graph without self loop is an (n-1)

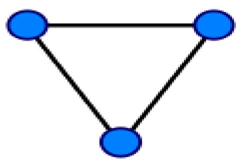


Fig. 3.2 Undirected Graphs

3.2 PROCEDURE OF GRAPH THEORETIC APPROACH

***Step 1*: -** First step of the Graph Theoretic approach is to make hierarchal diagram representing USM system. In this diagram system is divided into subsystems and subsystems into sub-subsystems in the form of branches of trees. That is why hierarchal diagram is also called tree diagram.

Step 2:- Second step is to make integrative block diagram. Although the tree diagram represents all the subsystems of USM system, but it fails to show the connectivity and interaction between different subsystems.

Step 3:- Although a pictorial representation of Graph is very convenient for visual study, other representations are better for computer processing. A matrix is convenient and useful way of representing Graph in the computer. *Third* step is to represent the graph in matrix form. There are two ways of representing the graph in matrix form i.e. incidence matrix and adjacency matrix.

Incidence matrix is an m*n rectangular matrix on which further processing cannot be done.

The adjacency matrix is also sometimes called connection matrix. It is somewhat more convenient to represent graph by adjacency matrix. It is an n*n square matrix. It is represented by A= $[a_{ij}]$ such that:

a_{ij} = 1 if subsystem i and subsystem j are connected

0 if subsystem i and subsystem j are not connected

Where i , j ε{ 1,2,3 ,….,n }

And i≠j

For a graph with no self loops, the adjacency matrix must have zeros (0's) on the diagonal. For an undirected graph, the connection matrix is symmetric. A self loop on the i^{th} Vertex corresponds to x_{11} = 1.

The definition of adjacency matrix is not used for the graph having parallel edges. This is why adjacency matrix X was defined for graphs without parallel edges. Adjacency matrix is more suitable for developing algebraic results.

Adjacency matrix A is representing the connectivity only.

Step 4:- Characteristic matrix B, for the graph developed for Ultrasonic Machining system is calculated as (λ I –A) where λ represents Eigen values for the matrix, I represent the identity matrix of the same order. It is developed as Adjacency matrix A represent the connectivity only, but it fails to represent ultrasonic machining system characteristic. As adjacency matrix is symmetric, these Eigen value are always real. Interdependencies between subsystems have been assigned value 0 and 1 depending on whether there is interaction or not. This does not represent varying degree of influence of one subsystem over other subsystem.

Step 5:- Variable characteristic matrix H is proposed as it is not there in mathematics. This matrix is able to represent the different characteristic of different subsystems. To develop this type of matrix consider a square matrix C with off diagonal elements e_{ij} representing the interaction between the subsystems. Consider another matrix D with diagonal elements S_i representing the different subsystems of USM. VCM – USM is represented as H= [D-C]. This matrix is used to represent the complete information about the subsystems and interactions between subsystems of an Ultrasonic Machining system. The determinant of the variable characteristic matrix H contains both positive and negative values. If the subsystems and interaction between subsystems is given a numerical value, information is lost because of negative signs. VCM is useful to give information only when the subsystem S_i and an interaction between the subsystems e_{ij} are in symbolic form.

Step 6:- To overcome the limitation of VCM another matrix called variable permanent matrix (VPM-USM) is proposed in order to retain the complete information of USM system. It is used in combinotrics/combinatorial mathematics/Discrete mathematics to study different combinations of different subsets i.e. systems. The permanent matrix is the standard matrix obtained by converting the negative signals from all the elements in VCM into positive ones. Permanent function is the standard function obtained similar to the determinant of VCM. The negative terms in determinant of VCM are replaced by the positive sign to stop the loss of information in the case when the subsystem and interaction between the subsystems are given a numerical value.

Step 7:- Make the physical /graphical representation of permanent function. Maximum number of terms in the permanent function depends on the number of subsystems into which system is divided. If there are n number of subsystems then maximum number of terms formed is **n!**. These terms depend on the interaction between the subsystems. As the interactions between the subsystems are reduced, the number of terms also reduces. A permanent function contains maximum (N+1) group where N represents the number of subsystems.

Step 8:- From the graphical representation of permanent function, the identification set of any USM system may be written as

$J_1/ J_2/ J_3/\ldots../ J_n$

Where J_k represent the total number of terms in the k^{th} Group and k= (1,2,3……., n)

They represent different structure conclusively.

Step 9:- The next step is to find coefficient of similarity and coefficient of dissimilarity. The coefficient of similarity and coefficient of dissimilarity gives a schematic method of comparison of different structures of the USM system.

Criteria 1:-

Coefficient of dissimilarity $C_{d-1} = \frac{\sum_k \phi_k}{Y_1}$

Where $\phi_k = J_k - J_k^{'}$

Where ϕ_k = the difference between no. of terms from the same group

Y_1 = max. $[\sum_k J_k \; and \; \sum_k J_k^{'}]$

The above criteria 1 developed is a simple method of quantifying structural difference between ultrasonic machining systems but this may cause loss of comparison information in the coefficient of dissimilarity. This is because of the fact that value of ϕ_k may be negative also depending upon structural differences in the ultrasonic machining system.

C_{s-1} = 1- $C_{d-`1}$

If C_{d-1} is negative i.e. C_{d-1} <0 then C_{s-1} > 1 which is not possible.

Step 10: - In order to avoid the above limitation 2^{nd} Coefficient of dissimilarity C_{d-2} is proposed

$C_{d-2} = [\frac{\sum_k \phi_k^2}{Y_2}]^{(1/2)}$

Y_2 = max. $[\sum_k J_k^2$ And$\sum_k J_k^{'2}]$

And $\phi_k = [J_k - J_k^{'}]$

C_{d-2} is positive always

Therefore 0< C_{s-2} < 1 as C_{s-2}= 1-C_{d-2}

Example 3.1

3.1.1

Step 1:- First step of Graph theoretic approach is to make a hierarchical tree diagram representing Ultrasonic machining system. An ultrasonic machining system is divided into four subsystems i.e. Input Source, Energy Source, Process Parameters Source and Output Source.

HIERARICHAL TREE SHOWING VARIOUS SUB – SYSTEMS

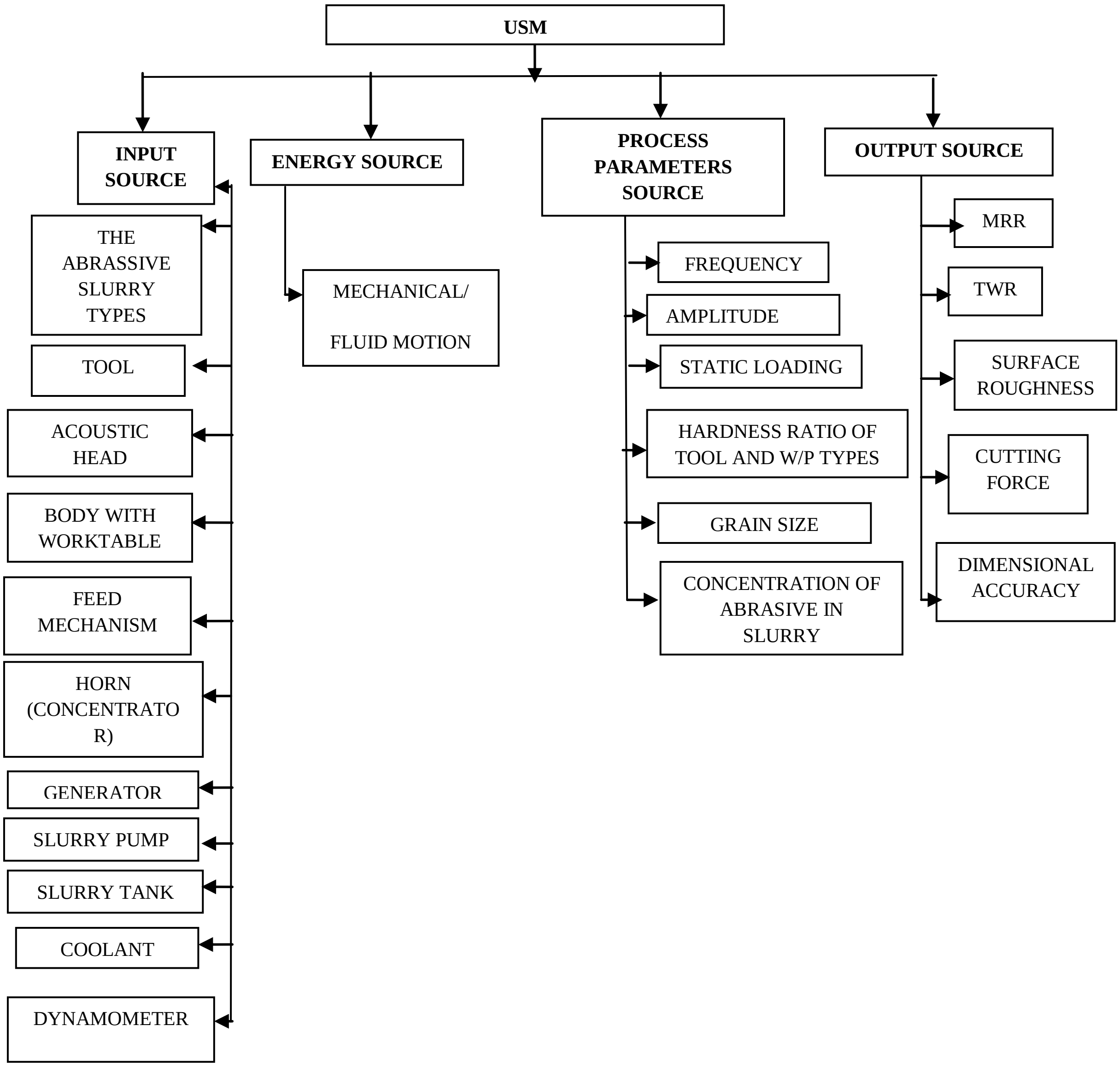


Fig. 3.3:- Hierarchal Tree Showing Various Systems of Ultrasonic Machining

Step 2:- As the hierarchal diagram fails to show connectivity and interaction between different subsystems. So the integrative block diagram is made in order to show connectivity and interaction between different subsystems.

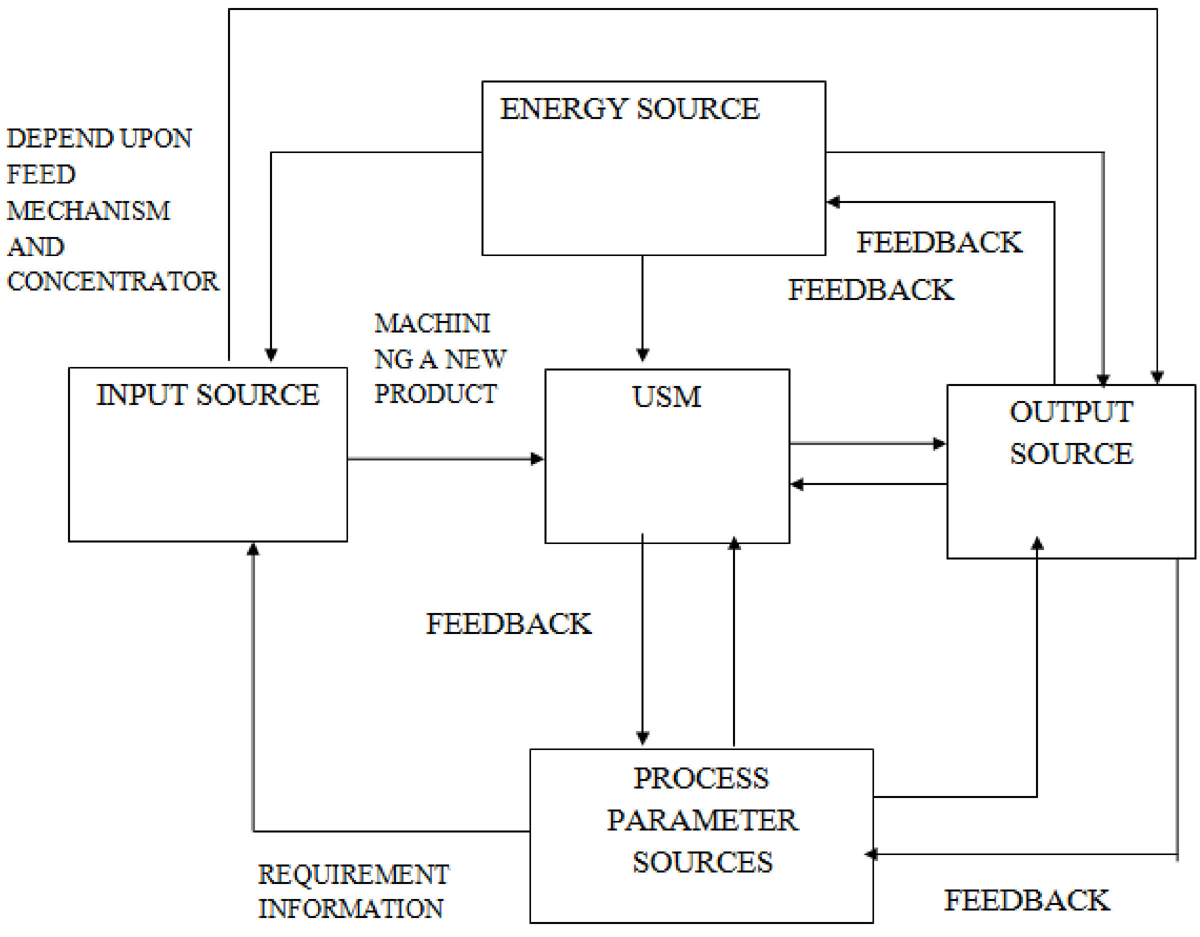


Fig. 3.4 Integrative Block Diagram of Ultrasonic Machining system

S_1 = Input Source

S_2 = Energy Source

S_3 = Process Parameter Sources

S_4 = Output Source

e_{ij}= interaction of subsystem S_i to subsystem S_j

L_{ijk} = interaction loop among subsystemsS_i ,S_j and S_k

A= ultrasonic machining system adjacency matrix

B= ultrasonic machining system characteristic matrix

H = ultrasonic machining system variable characteristic matrix

D = variable diagonal matrix.

C= interaction variable matrix.

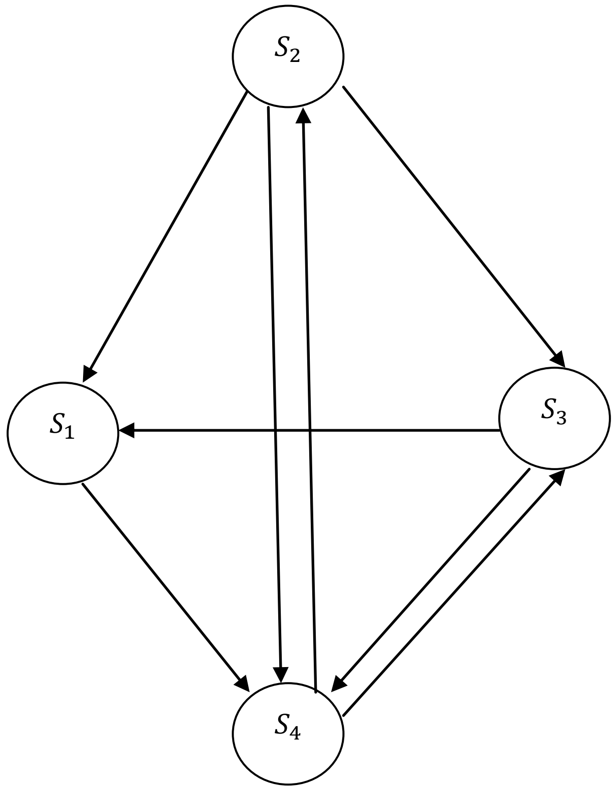


Fig. 3.5 Structural Graph of Ultrasonic machining system

Matrix Representation

Step 3:- *A* square matrix A= $[e_{ij}]$ of order 4 is constructed, the order depends upon the number of subsystems. Here e_{ij} represents the interaction of i^{th} subsystem with the j^{th} subsystem. If interaction is present then put the value 1 and if the interaction is not present then put the value 0. e_{ii} is zero because there is no self loop of any subsystem. The matrix for the graph shown in Fig 3.5 is given below in the equation (3.1)

$$A= \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix} \tag{3.1}$$

Step 4:- Characteristic matrix B, for the graph developed for USM is written as [λ I-A]

Where λ represents the Eigen values of the matrix; I represent the identity matrix of the same order as A. Characteristic matrix B is shown as below in equation (3.2)

$$B=\begin{bmatrix} \lambda & 0 & 0 & -1 \\ -1 & \lambda & -1 & -1 \\ -1 & 0 & \lambda & -1 \\ 0 & -1 & -1 & \lambda \end{bmatrix} \qquad (3.2)$$

In the above matrix the value of all diagonal elements are same. Interdependencies between subsystems have been assigned value 0 and 1 depending upon whether interaction is there or not. This does not represent varying degree of influence of one subsystem over other subsystem.

The determinant of ultrasonic machining system characteristic matrix B(3.2) is shown below in equation (3.3)

$$Det(B) = \lambda^4 - 2\lambda^2 - 3\lambda - 1 = 0 \qquad (3.3)$$

Step 5:- USM system variable characteristic matrix (VCM-USM)

This matrix is used to represent different features of different subsystems. To develop this type of matrix graph in Fig 3.5 used, consider a matrix C with off –diagonal elements e_{ij} , representing the interaction between the subsystems. Another matrix D is considered with diagonal elements S_i representing the different subsystems of USM system as shown in Fig 3.4. VCM-USM is represented as H= [D-C]. Variable characteristic matrix H is shown below in equation (3.4)

$$D=\begin{bmatrix} S_1 & 0 & 0 & 0 \\ 0 & S_2 & 0 & 0 \\ 0 & 0 & S_3 & 0 \\ 0 & 0 & 0 & S_4 \end{bmatrix}$$

$$C=\begin{bmatrix} 0 & e_{12} & e_{13} & e_{14} \\ e_{21} & 0 & e_{23} & e_{24} \\ e_{31} & e_{32} & 0 & e_{34} \\ e_{41} & e_{42} & e_{43} & 0 \end{bmatrix}$$

From Fig 3.5 we get

$$C=\begin{bmatrix} 0 & 0 & 0 & e_{14} \\ e_{21} & 0 & e_{23} & e_{24} \\ e_{31} & 0 & 0 & e_{34} \\ 0 & e_{42} & e_{43} & 0 \end{bmatrix}$$

H= [D-C]

$$H=\begin{bmatrix} S_1 & 0 & 0 & -e_{14} \\ -e_{21} & S_2 & -e_{23} & -e_{24} \\ -e_{31} & 0 & S_3 & -e_{34} \\ 0 & -e_{42} & -e_{43} & S_4 \end{bmatrix} \quad (3.4)$$

$$\text{Det (H)} = S_1 \begin{bmatrix} S_2 & -e_{23} & -e_{24} \\ 0 & S_3 & -e_{34} \\ -e_{42} & -e_{43} & S_4 \end{bmatrix} + (-1)^{1+4} (-e_{14}) \begin{bmatrix} -e_{21} & S_2 & -e_{23} \\ -e_{31} & 0 & S_3 \\ 0 & -e_{42} & -e_{43} \end{bmatrix}$$

The determinant of variable characteristic matrix H of ultrasonic machining system (3.4) is shown below in equation (3.5)

S_1 [S_2 (S_3S_4 - $e_{34}e_{43}$) + e_{23}(0-$e_{34}e_{42}$) $-e_{24}(S_3e_{42})$] + e_{14} [-e_{21}(0 + $e_{42}S_3$) - S_2 ($e_{31}e_{43}$-0) -e_{23} ($e_{31}e_{42}$ -0)]

$S_1S_2S_3S_4$ -$S_1S_2e_{34}e_{43}$ - $S_1e_{23}e_{34}e_{42}$ -$S_1S_3e_{24}e_{42}$- $S_3e_{14}e_{42}e_{21}$ - $S_2e_{31}e_{14}e_{43}$ - $e_{23}e_{31}e_{14}e_{43}$ (3.5)

It can be observed that the terms in multinomial of equation (3.5) can be rearranged in decreasing order of subsystems characteristic terms S_i's. Further it may be observed that a four subsystem matrix may be classified into five groups and is shown in equation (3.6(a))

[$S_1S_2S_3S_4$]+[-$S_1S_2e_{43}e_{43} - S_1S_3e_{24}e_{42}$]+[-$S_1e_{23}e_{34}e_{42} - S_3e_{14}e_{42}e_{21} - S_2e_{31}e_{14}e_{43}$]+[-$e_{23}e_{31}e_{14}e_{42}$] (3.6($a$))

The loops and dyads (interaction loop between two subsystems) in equation (3.6(a)) are written in more convenient way in equation (3.6(b))

[$S_1S_2S_3S_4$] +[-$S_1S_2L_{34} - S_1S_3L_{24}$] + [-$S_1L_{234}$ -S_3L_{142} -S_2L_{314}] +[-L_{2314}] (3.6(b))

Step 6:- Permanent matrix: - The permanent matrix is obtained when the negative sign from all the elements in the Variable characteristic matrix (VCM) in equation (3.4) are converted into the positive ones as shown below in the equation (3.7).

$$P = \begin{bmatrix} S_1 & 0 & 0 & e_{14} \\ e_{21} & S_2 & e_{23} & 0 \\ e_{31} & 0 & S_3 & e_{34} \\ 0 & e_{42} & e_{43} & S_4 \end{bmatrix} \quad (3.7)$$

The permanent function of the matrix P in equation (3.7) has been developed in equation (3.8)

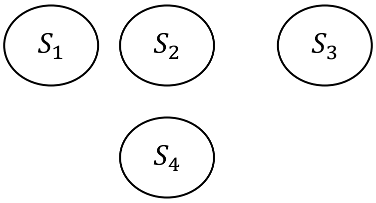
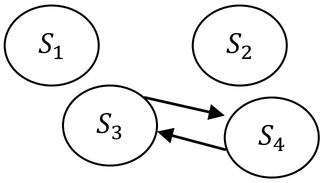
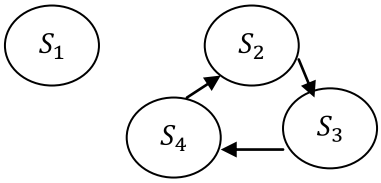
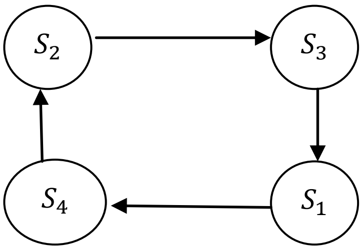
Per (P) = [$S_1S_2S_3S_4$] + [$S_1S_2L_{34} + S_1S_3L_{24}$] + [$S_1L_{234} + S_3L_{142} + S_2L_{314}$] + [$L_{2314}$] (3.8)

The numerical values may be assigned to various subsystems as well as their interaction with the help of knowledge of various experts in a single numerical value.S_1, S_2 , S_3, S_4may be obtained as:-

S_1 = Per (P_{S1}), S_2 = Per (P_{S2}), S_3 = Per (P_{S3}), S_4 = Per (P_{S4})

Step 7:- Graphical representation of permanent function. A permanent function contains maximum (N+1) group where N represents the number of subsystems. In this example permanent function contains 5 groups as the numbers of subsystems are 4

Table 3.1 Graphical representation of permanent function of Ultrasonic Machining System

First Group		Second Group	No term
Third Group	 + 1 more term	Fourth Group	 + 2 more terms
Fifth group			

The characteristic features of all the five groups of structural members of the ultrasonic machining system as identified in permanent function are summarized below:-

1) The first group consists of a single term representing a set of four subsystems individually representing each subsystem. The identification set is S_1 / S_2 /S_3/ S_4
2) The second group terms if exist should have three singular subsystems and a subsystem dependent on itself. Such condition is nonexistent in the ultrasonic machining system and thus the second group is found to be absent.
3) The third group has two terms consisting of two singular subsystems and a “two system loop” or a dyad.
4) The fourth group has three terms consisting of a set of one singular subsystem and three subsystem loop.

5) The fifth group has one term consists of four subsystem loop.

Step 8:- From the terms of permanent or the characteristic function, the identification set for an ultrasonic machining system may be written as shown below in the equation (3.9):-

$$J_1/J_2/J_3/J_4/J_5 = 1/0/2/3/1 \qquad (3.9)$$

3.1.2

Step 1:- The first step is same as discussed above in (Fig. 3.3)

Step 2:- *As* the hierarchal diagram fails to show connectivity and interaction between different subsystems. So the integrative block diagram is made in order to show connectivity and interaction between different subsystems. In the first integrative block diagram and this integrative block diagram the only difference is that in this integrative diagram Fig. 3.6 there is no feedback from the output source to the energy source.

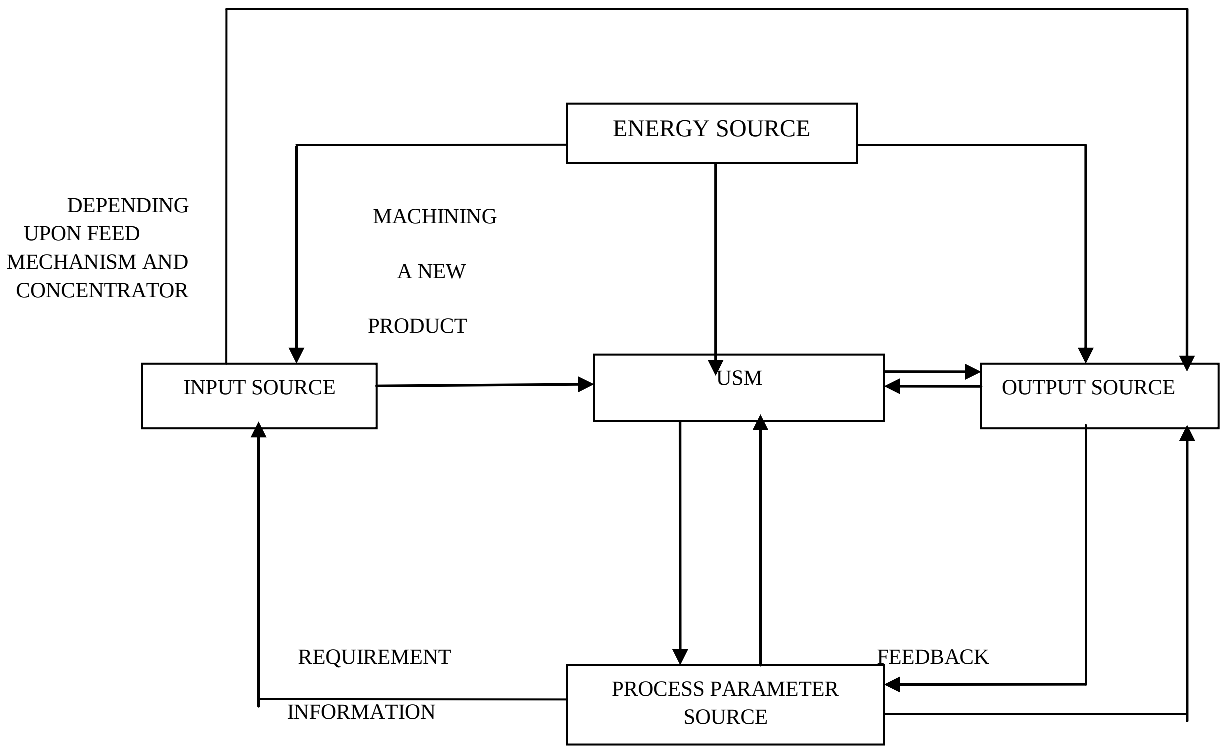


Fig. 3.6 Integrative Block Diagram of USM system

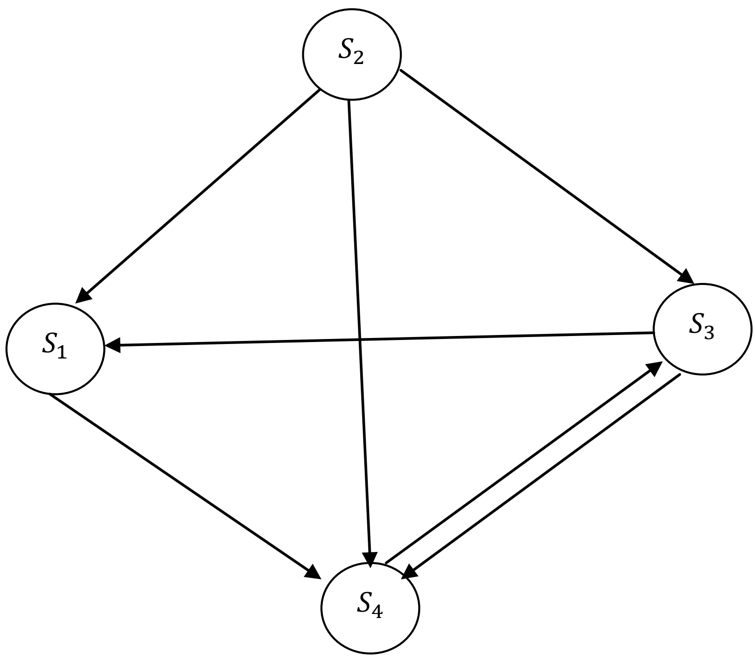


Fig. 3.7 Structural Graph of USM system

Matrix Representation

Step 3:- *A* square matrix A= $[e_{ij}]$ of order 4 is constructed, the order depends upon the number of subsystems. Here e_{ij} represents the interaction of i^{th} subsystem with the j^{th} subsystem. If interaction is present then put the value 1 and if the interaction is not present then put the value 0. e_{ii} is zero because there is no self loop interaction of any subsystem. Matrix for the graph shown in fig 3.7 is given below in equation (3.10) :-

$$A=\begin{bmatrix}0 & 0 & 0 & 1\\ 1 & 0 & 1 & 1\\ 1 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix} \qquad (3.10)$$

Step 4:- Characteristic matrix B, for the graph developed for USM is written as [λ I-A]

Where λ represents the Eigen values of the matrix; I represent the identity matrix of the same order as A. Characteristic matrix B is shown below in the equation (3.11)

$$B=\begin{bmatrix}\lambda & 0 & 0 & -1\\ -1 & \lambda & -1 & -1\\ -1 & 0 & \lambda & -1\\ 0 & 0 & -1 & \lambda\end{bmatrix} \qquad (3.11)$$

In the above matrix the value of all diagonal elements are same. Interdependencies between subsystems have been assigned value 0 and 1 depending upon whether there is interaction or not. This does not represent varying degree of influence of one subsystem over other subsystem.

The determinant of USM system characteristic matrix B (3.11) is shown below in equation (3.12)

$$\text{Det (B)} = \lambda^4 - \lambda^2 - \lambda = 0 \qquad (3.12)$$

Step 5:- USM system variable characteristic matrix (VCM-USM)

This matrix is used to represent different features of different subsystems. To develop this type of matrix graph in Fig 3.7 used consider a matrix C with off –diagonal elements e_{ij} , representing the interaction between the subsystems. Another matrix D is considered with diagonal elements S_i representing the different subsystems of USM as shown in fig 3.6 VCM-USM is represented as H= [D-C]. Variable characteristic matrix H is shown below in equation (3.13)

$$D=\begin{bmatrix} S_1 & 0 & 0 & 0 \\ 0 & S_2 & 0 & 0 \\ 0 & 0 & S_3 & 0 \\ 0 & 0 & 0 & S_4 \end{bmatrix}$$

$$C=\begin{bmatrix} 0 & 0 & 0 & e_{14} \\ e_{21} & 0 & e_{23} & e_{24} \\ e_{31} & 0 & 0 & e_{34} \\ 0 & 0 & e_{43} & 0 \end{bmatrix}$$

$$H = [D\text{-}C] = \begin{bmatrix} S_1 & 0 & 0 & -e_{14} \\ -e_{21} & S_2 & -e_{23} & -e_{24} \\ -e_{31} & 0 & S_3 & -e_{34} \\ 0 & 0 & -e_{43} & S_4 \end{bmatrix} \quad (3.13)$$

The determinant of variable characteristic matrix H of USM system (3.13) is shown below in equation (3.14)

$$\text{Det (H)} = S_1 \begin{bmatrix} S_2 & -e_{23} & -e_{24} \\ 0 & S_3 & -e_{34} \\ 0 & -e_{43} & S_4 \end{bmatrix} + (-1)^{(1+4)} \; (-e_{14}) \begin{bmatrix} -e_{21} & S_2 & -e_{23} \\ -e_{31} & 0 & S_3 \\ 0 & 0 & -e_{43} \end{bmatrix}$$

$$= S_1[S_2(S_3S_4 - e_{43}e_{34}) + e_{23}(0) + (-e_{24})(0)] + e_{14}[-e_{21}(0) + (-S_2)(e_{31}e_{43}) + (-e_{23})(0)]$$

$$= S_1S_2S_3S_4 - S_1S_2e_{34}e_{43} - S_2e_{31}e_{14}e_{43} \quad (3.14)$$

It can be observed that the terms in multinomial of equation (3.14) can be rearranged in decreasing order of subsystems characteristic terms S_i's. Further it may be observed that a four subsystem matrix may be classified into five groups and is shown in equation (3.15(a))

$$[S_1S_2S_3S_4]+[-S_1S_2e_{34}e_{43}]+[-S_2e_{31}e_{14}e_{43}] \quad (3.15(a))$$

The loops and dyads (interaction loop between two subsystems) in equation (3.15(a)) are written in more convenient way in equation (3.15(b))

$$= S_1S_2S_3S_4 - S_1S_2L_{34} - S_2L_{314} \quad (3.15(b))$$

***Step 6:* -** Permanent matrix: - The permanent matrix is obtained when the negative sign from all the elements in the Variable characteristic matrix (VCM) in equation (3.13) are converted into the positive ones as shown below in the equation (3.16).

$$P=\begin{bmatrix} S_1 & 0 & 0 & e_{14} \\ e_{21} & S_2 & e_{23} & 0 \\ e_{31} & 0 & S_3 & e_{34} \\ 0 & 0 & e_{43} & S_4 \end{bmatrix} \qquad (3.16)$$

The permanent function of the matrix P in equation (3.16) has been developed in equation (3.17)

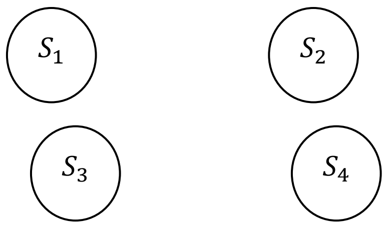
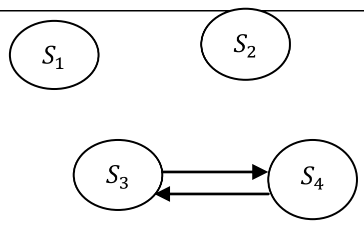
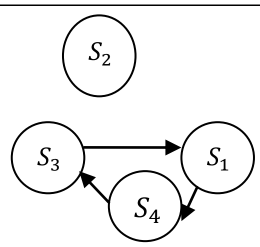
$$\text{Per (P)} = S_1S_2S_3S_4 + S_1S_2L_{34} + S_2L_{314} \qquad (3.17)$$

The numerical values may be assigned to various subsystems as well as their interaction with the help of knowledge of various experts in a single numerical value.S_1, S_2 , S_3, S_4may be obtained as:-

S_1 = Per (P_{S1}) , S_2 = Per (P_{S2}) , S_3 = Per (P_{S3}) , S_4 = Per (P_{S4})

Step 7:- Graphical representation of permanent function. A permanent function contains maximum (N+1) group where N represents the number of subsystems. In this example permanent function contains 5 groups as the numbers of subsystems are 4

Table 3.2 Graphical representation of permanent function of USM system

First Group		Second Group	-
Third Group		Fourth Group	
Fifth Group	-		

The characteristic features of all the five groups of structural members of the ultrasonic machining system as identified in permanent function are summarized below:-

1) The first group consists of a single term representing a set of four subsystems individually representing each subsystem. The identification set is S_1 / S_2 /S_3/ S_4
2) The second group terms if exist should have three singular subsystems and a subsystem dependent on itself. Such condition is nonexistent in the ultrasonic machining system and thus the second group is found to be absent.
3) The third group has one term consists of two singular subsystems and a "two system loop" or a dyad.
4) The fourth group has three terms consists of a set of one singular subsystem and three subsystem loop.
5) The fifth term is absent as there is no interaction between Subsystem S_2/S_1 / S_3 / S_4

Step 8:- From the terms of permanent or the characteristic function, the identification set for an ultrasonic machining system may be written as shown below in the equation (3.18):-

$$J_1 / J_2 / J_3 / J_4 / J_5 = 1/0/1/1/0 \quad (3.18)$$

Step 9:- The next step is to find coefficient of similarity and dissimilarity. It is used in comparing the two ultrasonic machining systems as shown below.

Coefficient of dissimilarity C_{d-1} is calculated as shown below in equation (3.19)

$$\text{Coefficient of dissimilarity } C_{d-1} = \frac{\sum_k \phi_k}{Y_1} \quad (3.19)$$

Where $\phi_k = J_k - J'_k$

Where ϕ_k = difference between no. of terms from the same group

ϕ_k = (1-1) + (0-0) + (2-1) + (3-1) + (1-0)

ϕ_k = 4

Y_1 = max. [$\sum_k J_k \; and \; \sum_k J'_k$]

Y_1 = max. [(1+0+2+3+1) and (1+0+1+1+0)]

Y_1 = max. [7 and 3]

Y_1 = 7

$$\text{Coefficient of dissimilarity } C_{d-1} = \frac{\sum_k \phi_k}{Y_1}$$

Coefficient of dissimilarity C_{d-1} = (4)/7 =0.57

Coefficient of similarity C_{s-1} is calculated as shown below in equation (3.20)

Coefficient of similarity C_{s-1} = 1-C_{d-1} (3.20)

C_{s-1} = 1- 0.57

C_{s-1} = 0.43

Step 10:- Second coefficient of similarity and variation is calculated.

Second Coefficient of dissimilarity C_{d-2} is calculated as shown below in equation (3.21)

$$C_{d-2} = \left[\frac{\sum_k \phi_k^2}{Y_2}\right]^{(1/2)} \quad (3.21)$$

And $\phi_k = [J_k - J'_k]$

$\sum_k \phi_k^2$ = $(1\text{-}1)^2 + (0\text{-}0)^2 + (2\text{-}1)^2 + (3\text{-}1)^2 + (1\text{-}0)^2$

=6

Y_2 = max. [$\sum_k J_k^2$ And$\sum_k J_k'^2$]

Y_2 = max. [$(1^2 + 0^2 + 2^2 + 3^2 + 1^2)$ and $(1^2 + 0^2 + 1^2 + 1^2 + 0^2)$]

Y_2 = max. [15 and 3]

Y_2 = 15

C_{d-2} = $(6/15)^{(1/2)}$

C_{d-2} = 0.632

Second Coefficient of similarity C_{s-2} is calculated as shown below in equation (3.22)

C_{s-2} = 1- C_{d-2} (3.22)

1- 0.632

=0.368

Example 3.2

3.2.1

Step1: - First step of Graph theoretic approach is to make a hierarchical tree diagram representing Micro ultrasonic machine with tool vibration. A micro ultrasonic machine with tool vibration is divided into three subsystem i.e. Ultrasonic spindle system, Slurry supply system and data Acquisition system

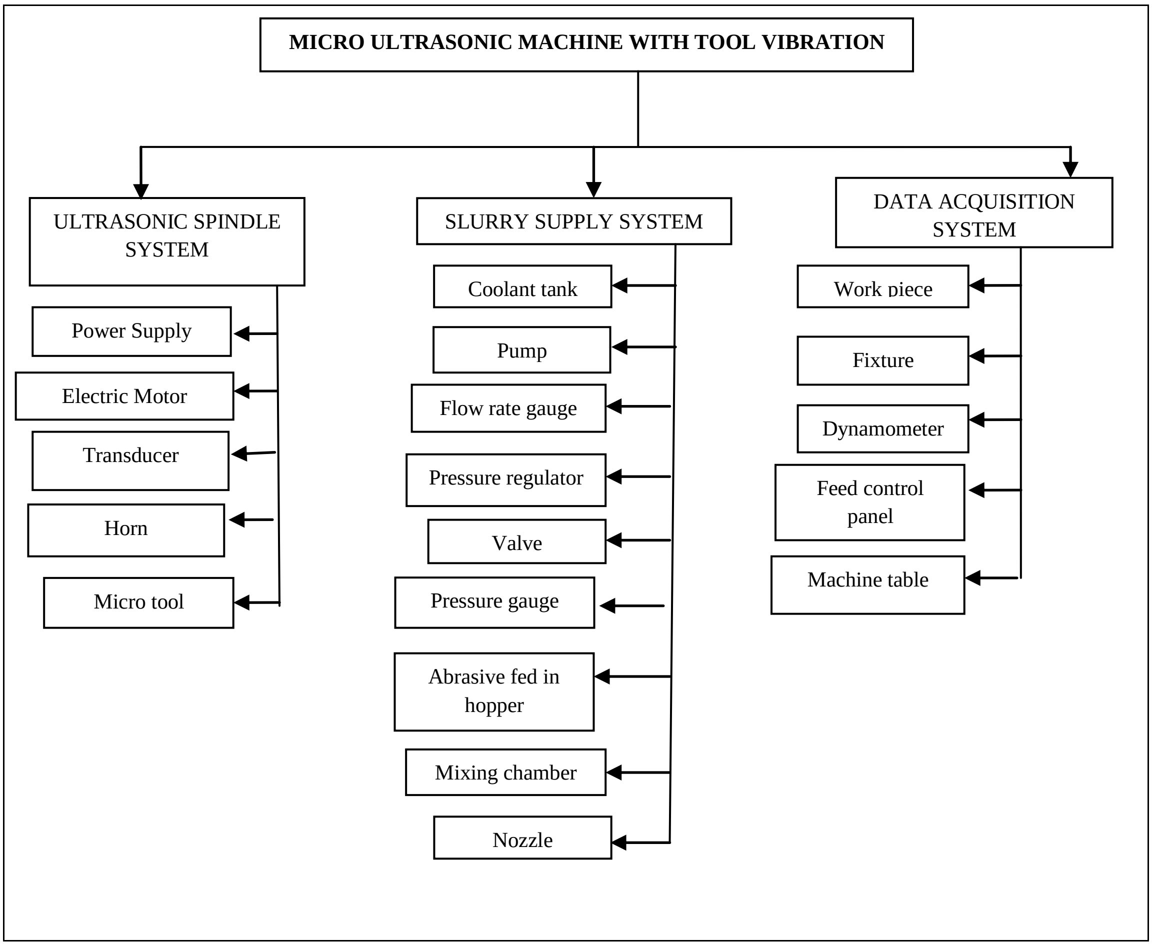


Fig. 3.8 Hierarchal Diagram of Micro USM with Tool Vibration

Step 2: - The second step is to make an integrative block diagram between three subsystems i.e. Ultrasonic spindle system, Slurry supply system and data Acquisition system. As the hierarchical diagram fails to show interaction between subsystems.

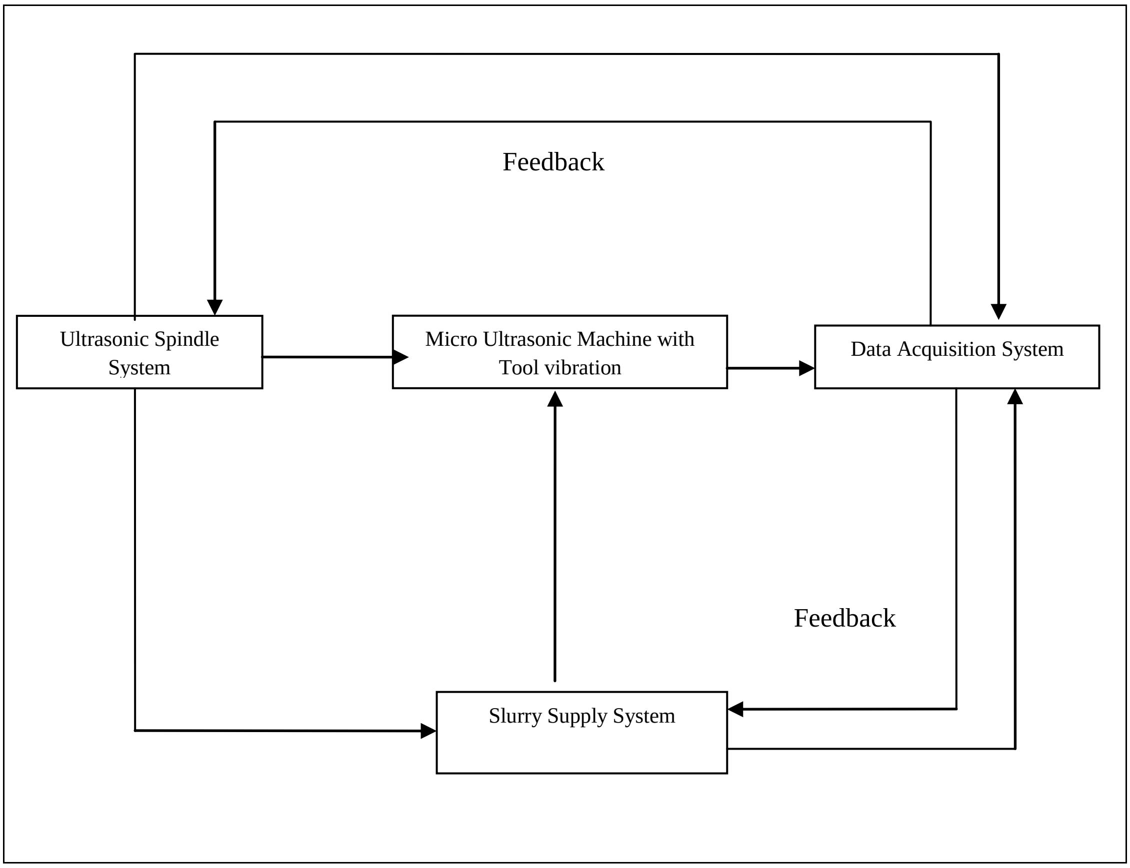


Fig. 3.9 Integrative Block Diagram of Micro USM with Tool Vibration

S_1 = Ultrasonic spindle system

S_2 = Slurry Supply System

S_3 = Data Acquisition system

e_{ij} = interaction of micro ultrasonic machining subsystem S_i to micro ultrasonic machining subsystem S_j

L_{ijk} = interaction loop among micro ultrasonic machining subsystems S_i, S_j, S_k

A = micro ultrasonic machining system adjacency matrix

B= micro ultrasonic machining system characteristic matrix

H = micro ultrasonic machining system variable characteristic matrix

D= micro ultrasonic machining system variable diagonal matrix

C= micro ultrasonic machining system interaction variable matrix.

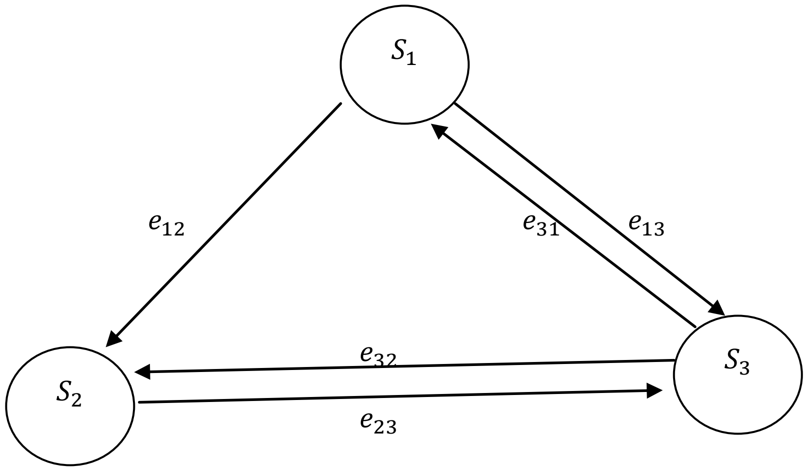


Fig. 3.10 Structural Graph of Micro USM with Tool Vibration

***Step 3:* -** Third step is to make adjacency matrix. It only shows the connectivity between three subsystems i.e. ultrasonic spindle system, Slurry supply system and data Acquisition system.

The Adjacency matrix A= $[a_{ij}]$ is a matrix such that

$a_{ij=}$ 1 if subsystem i and subsystem j are connected

= 0 if subsystem i and subsystem j are not connected

The Adjacency matrix A of Micro USM with tool vibration (Fig. 3.10) is shown below in the equation (3.23)

$$A=\begin{bmatrix}0 & 1 & 1\\ 0 & 0 & 1\\ 1 & 1 & 0\end{bmatrix} \qquad (3.23)$$

***Step 4:* -** Characteristic matrix B for Micro ultrasonic machining with tool vibration is calculated from Adjacency matrix A as (λ I – A) where λ represent the Eigenvalue for the matrix and I represent the identity matrix with the same order as that of A i.e. 3 The characteristic matrix B of Micro USM with tool vibration is shown below in the equation (3.24)

B= [λ I - A]

$$B=\begin{bmatrix}\lambda & -1 & -1\\ 0 & \lambda & -1\\ -1 & -1 & \lambda\end{bmatrix} \qquad (3.24)$$

In the above matrix the value of all diagonal elements are same. Interdependencies between subsystems have been assigned value 0 and 1 depending upon whether there is interaction or not. This does not represent varying degree of influence of one subsystem over other subsystem.

The determinant of Micro USM with tool vibration characteristic matrix B (3.24) is shown below in equation (3.25)

$$Det(B) = \lambda^3 - 2\lambda - 1 = 0 \quad (3.25)$$

Step 5: - Variable characteristic matrix H is proposed. To develop this matrix consider a square matrix C with off diagonal elements e_{ij} representing the interaction between the subsystems and another matrix D with diagonal elements $S_i's$ representing the different subsystems of Micro USM. VCM is calculated as H= [D-C]. This matrix is used to represent the complete information about the 3 subsystems and interactions between them. Variable characteristic matrix H is shown below in equation (3.26)

$$D=\begin{bmatrix} S_1 & 0 & 0 \\ 0 & S_2 & 0 \\ 0 & 0 & S_3 \end{bmatrix}$$

$$C=\begin{bmatrix} 0 & e_{12} & e_{13} \\ 0 & 0 & e_{23} \\ e_{31} & e_{32} & 0 \end{bmatrix}$$

H= [D-C]

$$H=\begin{bmatrix} S_1 & -e_{12} & -e_{13} \\ 0 & S_2 & -e_{23} \\ -e_{31} & -e_{32} & S_3 \end{bmatrix} \quad (3.26)$$

The determinant of variable characteristic matrix H of Micro USM with tool vibration (3.26) is shown below in equation (3.27)

$$Det(H) = S_1S_2S_3 - S_1e_{23}e_{32} - S_2e_{13}e_{31} - e_{23}e_{31}e_{12} \quad (3.27)$$

It can be observed that the terms in multinomial of equation (3.27) can be rearranged in decreasing order of subsystems characteristic termsS_i's. Further it may be observed that a three subsystem matrix may be classified into four groups and is shown in equation $(3.28(a))$

$$Det[H] = [S_1 S_2S_3] + [- S_1e_{23}e_{32} - S_2e_{13}e_{31}] + [- e_{23}e_{31}e_{12}] \quad (3.28(a))$$

The loops and dyads (interaction loop between two subsystems) in equation $(3.28(a))$are written in more convenient way in equation $(3.28(b))$

$$Det[H] = [S_1S_2S_3] + [-S_1L_{23}-S_2L_{13}] + [-L_{123}] \quad (3.28(b))$$

Step 6:- Variable permanent matrix (VPM-USM) is proposed in order to retain the complete information of Micro ultrasonic machine with tool vibration. The permanent matrix is obtained when the negative sign from all the elements in the Variable characteristic matrix (VCM) in equation (3.26) are converted into the positive ones as shown below in the equation (3.29).

$$P=\begin{bmatrix} S_1 & e_{12} & e_{13} \\ 0 & S_2 & e_{23} \\ e_{31} & e_{32} & S_3 \end{bmatrix} \quad (3.29)$$

The permanent function of the matrix P in equation (3.29) has been developed in equation (3.30)

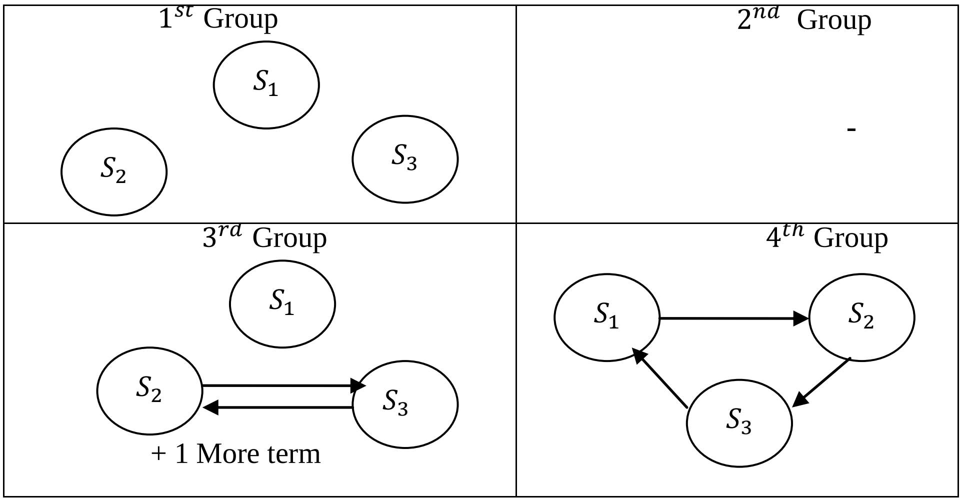
$$\text{Per (P)} = [S_1 S_2 S_3] + [S_1 e_{23} e_{32} + S_2 e_{13} e_{31}] + [e_{12} e_{23} e_{31}] \quad (3.30)$$

The numerical values may be assigned to various micro ultrasonic machining subsystems as well as their interaction with the help of knowledge of various experts in a single numerical value. S_1, S_2 , S_3 may be obtained as:-

S_1 = Per (P_{S1}) , S_2 = Per (P_{S2}) , S_3 = Per (P_{S3})

Step 7: - Physical representation is made of a permanent function. Maximum number of terms in the permanent function depends on the number of subsystems into which system is divided. A permanent function contains maximum 4 groups as the numbers of subsystems are 3.

Table 3.3 Graphical representation of permanent function of Micro ultrasonic machining system with tool vibration



The features of all the four groups of structural members of the Micro ultrasonic machining with tool vibration as identified in permanent function are summarized below:-

1) The first group consists of single term representing a set of three subsystems individually representing each subsystem. The identification set is S_1 / S_2 /S_3.
2) The second group terms if exist should have two singular subsystems and a subsystem dependent on itself. Such condition is nonexistent in the Micro

ultrasonic machining with tool vibration and thus the second group is found to be absent.

3) The third group has two terms consists of a set of one singular subsystems and a "two system loop" or a dyad.
4) The fourth group has one term consists of three subsystem loop.

Step 8: - From the terms of permanent or the characteristic matrix, the identification set for a Micro ultrasonic machine with tool vibration may be written as shown below in the equation (3.31):-

$$J_1 / J_2 / J_3 / J_4 = 1/0/2/1 \quad (3.31)$$

3.2.2

Step 1: - First step of Graph theoretic approach is to make a hierarchical tree diagram representing Micro ultrasonic machine with work piece vibration. A micro ultrasonic machine with tool vibration is divided into three subsystem i.e. Power supply system, slurry supply system and work piece vibration system.

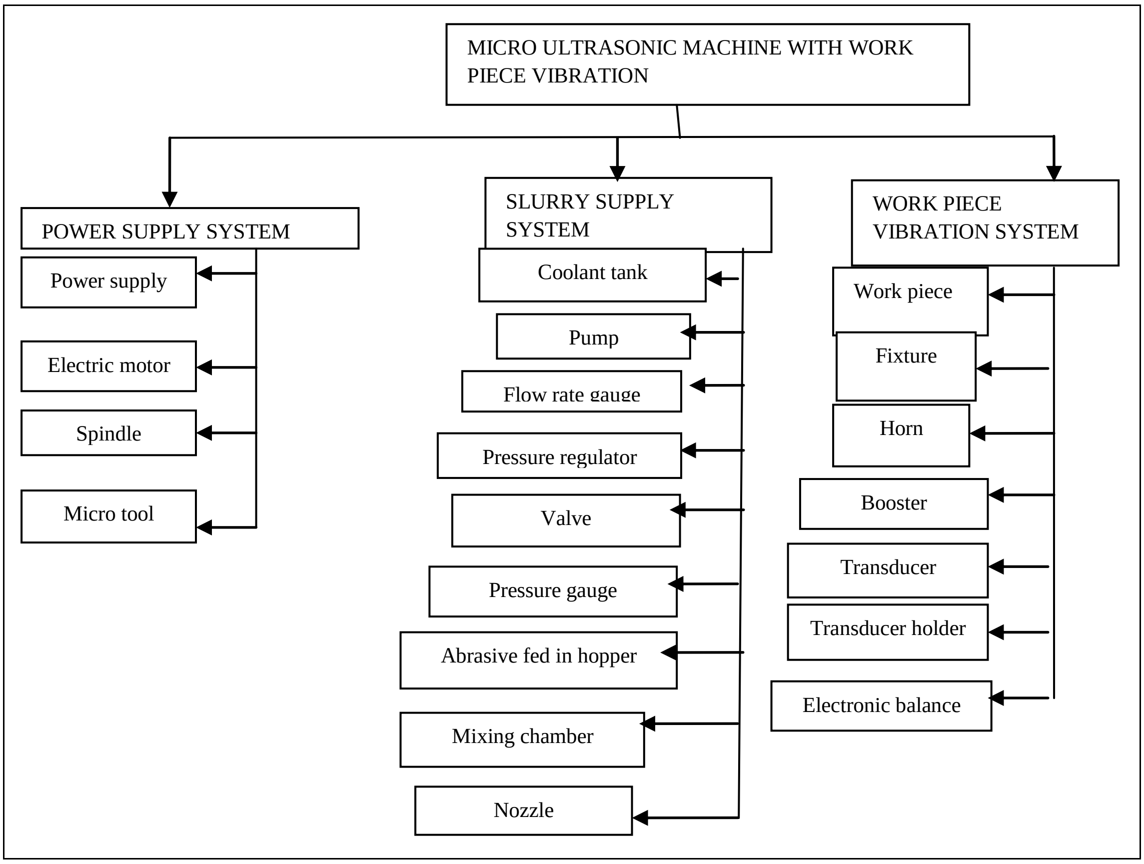


Fig. 3.11 Hierarchal Diagram of Micro USM with Work piece Vibration

Step 2:- The second step is to make an integrative block diagram between the subsystems i.e. Power supply system, slurry supply system and work piece vibration system. As the hierarchical diagram fails to show interaction and connectivity between subsystems.

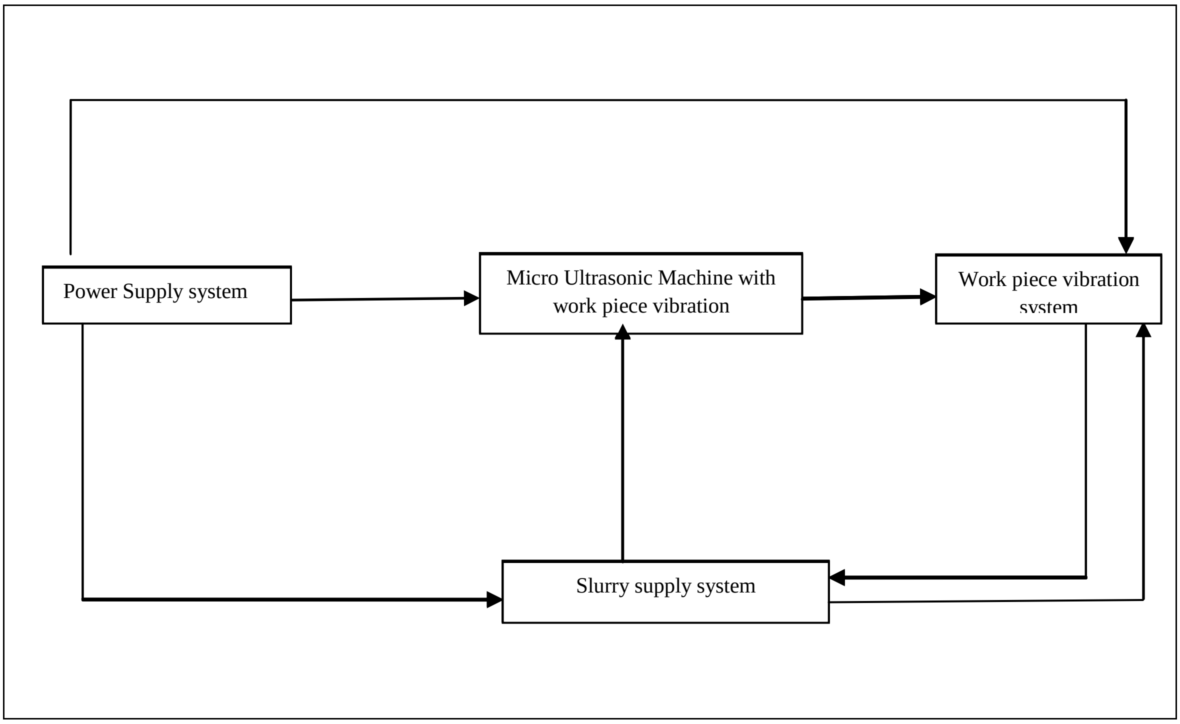


Fig. 3.12 Integrative Block Diagram of Micro USM with Work piece Vibration

S_1 = Power Supply System

S_2 = Slurry Supply System

S_3 = Work piece vibration system

e_{ij} = interaction of micro ultrasonic machining subsystem S_i to micro ultrasonic machining subsystem S_j

L_{ijk} = interaction loop among micro ultrasonic machining subsystems S_i, S_j, S_k

A = micro ultrasonic machining system adjacency matrix

B= micro ultrasonic machining system characteristic matrix

H = micro ultrasonic machining system variable characteristic matrix

D= micro ultrasonic machining system variable diagonal matrix

C= micro ultrasonic machining system interaction variable matrix.

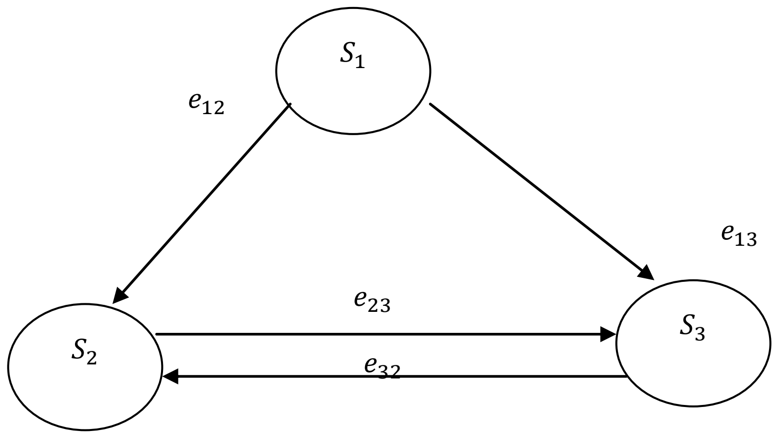


Fig. 3.13 Structural Graph of Micro USM with Work piece Vibration

Step 3: - Third step is to make adjacency matrix. It only shows the connection between the subsystems i.e. Power supply system, slurry supply system and work piece vibration system.

The Adjacency matrix A= $[a_{ij}]$ is a matrix such that

$a_{ij=}$ 1 if subsystem i and subsystem j are connected

= 0 if subsystem i and subsystem j are not connected

The Adjacency matrix A of Micro USM with Work piece vibration (Fig. 3.13) is shown below in the equation (3.32)

$$A=\begin{bmatrix}0 & 1 & 1\\0 & 0 & 1\\0 & 1 & 0\end{bmatrix} \quad (3.32)$$

Step 4: - Characteristic matrix B for Micro ultrasonic machining with work piece vibration is calculated from Adjacency matrix A as (λ I – A) where λ represent the Eigen value for the matrix and I represent the identity matrix with the same order as that of A i.e. 3. The characteristic matrix B of Micro USM with work piece vibration is shown below in the equation (3.33)

B= [λ I - A]

$$B=\begin{bmatrix}\lambda & -1 & -1\\0 & \lambda & -1\\0 & -1 & \lambda\end{bmatrix} \quad (3.33)$$

In the above matrix the value of all diagonal elements are same. Interdependencies between subsystems have been assigned value 0 and 1 depending upon whether there is interaction or not. This does not represent varying degree of influence of one subsystem over other subsystem.

The determinant of Micro USM with tool vibration characteristic matrix B (3.33) is shown below in equation (3.34)

Det (B) = λ^3-1 (3.34)

Step 5: **-** Variable characteristic matrix H is proposed. To develop this matrix, consider a square matrix C with off diagonal elements e_{ij} representing the interaction between the subsystems and another matrix D with diagonal elements S_i representing the different subsystems of Micro USM. VCM is calculated as H= [D-C]. This matrix is used to represent the complete information about the 3 subsystems and interactions between them. Variable characteristic matrix H is shown below in equation (3.35)

$$D=\begin{bmatrix} S_1 & 0 & 0 \\ 0 & S_2 & 0 \\ 0 & 0 & S_3 \end{bmatrix}$$

$$C=\begin{bmatrix} 0 & e_{12} & e_{13} \\ 0 & 0 & e_{23} \\ 0 & e_{32} & 0 \end{bmatrix}$$

H= [D-C]

$$H= [D - C] = \begin{bmatrix} S_1 & -e_{12} & -e_{13} \\ 0 & S_2 & -e_{23} \\ 0 & -e_{32} & S_3 \end{bmatrix} \qquad (3.35)$$

The determinant of variable characteristic matrix H of Micro USM with work piece vibration (3.35) is shown below in equation (3.36)

Det (H) = $S_1S_2S_3$ - $S_1e_{23}e_{32}$ (3.36)

It can be observed that the terms in multinomial of equation (3.36) can be rearranged in decreasing order of subsystems characteristic termsS_i's. Further it may be observed that a three subsystem matrix may be classified into four groups and is shown in equation $(3.37(a))$

$$H=[S_1S_2S_3 \ ] + [- S_1e_{23}e_{32}] \qquad (3.37(a))$$

The loops and dyads (interaction loop between two subsystems) in equation $(3.37(a))$ are written in more convenient way in equation $(3.37(b))$

$$H= [S_1S_2S_3 \ ] + [-S_1L_{23} \ ] \qquad (3.37(b))$$

Step 6: **-** Variable permanent matrix (VPM-USM) is proposed in order to retain the complete information of Micro ultrasonic machine with work piece vibration. Permanent matrix is shown below in the equation (3.38)

$$P = \begin{bmatrix} S_1 & e_{12} & e_{13} \\ 0 & S_2 & e_{23} \\ 0 & e_{32} & S_3 \end{bmatrix} \qquad (3.38)$$

The permanent function of the matrix P in equation (3.38) has been developed in equation (3.39)

$$\text{Per (P)} = [S_1 S_2 S_3\ ] + [S_1 e_{23} e_{32}\ ] \qquad (3.39)$$

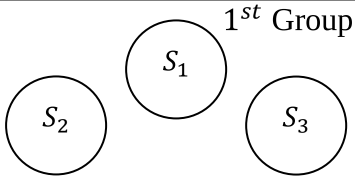
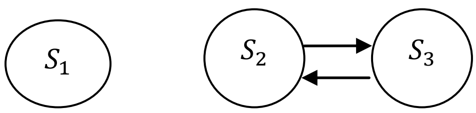
$$= [S_1 S_2 S_3] + [S_1 L_{23}]$$

The numerical values may be assigned to various micro ultrasonic machining subsystems as well as their interaction with the help of knowledge of various experts in a single numerical value.S_1, S_2 , S_3 may be obtained as:-

S_1 = Per (P_{S1}), S_2 = Per (P_{S2}), S_3 = Per (P_{S3})

Step 7: **-** Physical representation is made of a permanent function. Maximum number of terms in the permanent function depends on the number of subsystems into which system is divided. A permanent function contains maximum 4 groups as the numbers of subsystems are 3.

Table 3.4 Graphical representation of permanent function of Micro ultrasonic machining system with work piece vibration

1^{st} Group 	2^{nd} Group -
3^{rd} Group 	4^{th} Group -

The features of all the four groups of structural members of the Micro ultrasonic machine with work piece vibration as identified in permanent function are summarized below:-

1) The first group consists of single term representing a set of three subsystems individually representing each subsystem. The identification set is S_1 / S_2 /S_3.

2) The second group terms if exist should have two singular subsystems and a subsystem dependent on itself. Such condition is nonexistent in the Micro ultrasonic machine with work piece vibration and thus the second group is found to be absent.
3) The third group has two terms consists of a set of one singular subsystems and a “two system loop” or a dyad.
4) The fourth group if exist should have three subsystem loop and fourth group is absent in this case.

***Step 8:* -** From the terms of permanent or the characteristic matrix, the identification set for a Micro ultrasonic machine with work piece vibration may be written as shown below in the equation (3.40):-

$$J_1/J_2/J_3/J_4 = 1/0/1/0 \qquad (3.40)$$

***Step 9:* -** The next step is to find coefficient of similarity and coefficient of dissimilarity. It is used in the comparing two Micro ultrasonic machining systems as shown below.

Coefficient of dissimilarity C_{d-1} is calculated as shown below in equation (3.41)

Coefficient of dissimilarity (C_{d-1}) = $\frac{[(\Sigma \phi_k)]}{Y_1}$ (3.41)

$\phi_k = (J_k - J_k')$

Where ϕ_k = the difference between no. of terms from the same group

$\sum\phi_k = (1-1) + (0-0) + (2-1) + (1-0)$

$\sum\phi_k = 2$

$Y_1 = \max\left(\sum_k J_k,\ \sum_{k'} J_{k'}\right)$

$Y_1 = \max((1+0+2+1), (1+0+1+0))$

$Y_1 = \max(4, 2)$

$Y_1 = 4$

Coefficient of dissimilarity (C_{d-1}) = $\frac{[(\Sigma \phi_k)]}{Y_1}$

C_{d-1} = 2/4= 0.5

Coefficient of similarity C_{s-1} is calculated as shown below in equation (3.42)

Coefficient of similarity (C_{s-1}) = 1- C_{d-1} (3.42)

C_{s-1} = 1-0.5 =0.5

Step 10: - Second coefficient of similarity and dissimilarity is calculated as shown below in the equation (3.44) and (3.43) respectively.

$$C_{d-2} = [\frac{(\sum_k \phi_k^2)}{Y_2}]^{1/2} \qquad (3.43)$$

$$\phi_k = [J_k - J'_k\,]$$

$$Y_2 = \text{max.}(\sum_k J_k^2, \sum_k {J'_k}^2\ )$$

$$\sum_k \phi_k^2 = (1\text{-}1)^2 + (0\text{-}0)^2 + (2\text{-}1)^2 + (1\text{-}0)^2$$

$$=2$$

$$Y_2 = \max\left((1^2 + 0^2 + 2^2 + 1^2\,), (1^2 + 0^2 + 1^2 + 0^2)\right)$$

$$Y_2 = \max\,(6,2)$$

$$Y_2 = 6$$

$$C_{d-2} = \sqrt[2]{\frac{2}{6}} = 0.574$$

$$C_{s-2} = 1\text{-}C_{d-2} \qquad (3.44)$$

$$C_{s-2} = 1\text{-}0.574$$

$$C_{s-2} = 0.426$$

CHAPTER 4

MADM TECHNIQUE

4.1 INTRODUCTION

The MADM method is proposed to find out the best possible ultrasonic machining system from alternatives available in the market.

MADM TECHNIQUE

MADM is an approach employed to solve problems involving selection from the finite number of alternatives. An MADM method specifies how attribute information is to be processed in order to arrive at a choice. MADM techniques present the selection of an alternative from a set of alternatives based on prioritized attributes of the alternatives. The complexity of the problem can be better appreciated when one realizes that there are over 50 attributes that have to be considered in the selection of system for a particular application.

4.2 OBJECTIVE OF MADM TECHNIQUE

The objectives of MADM technique are:-

1. It gives the optimum selection of desirable attribute from a large number of attributes.
2. MADM gives alternatives for machining.
3. By MADM process we can modify attributes with changing technology.
4. By MADM process we know the market trend.

`

4.3 Identification of attributes for Ultrasonic Machining system

The attributes are categorized under the following headings i.e. Tool, Abrasive , Slurry ,Data Acquisition system, coolant system, process parameters, performance parameters, input parameters. A proper identification of ultrasonic machining attribute is critically important as attribute provides a means of evaluating levels of an objective. Each alternative of USM can be characterized by number of attributes. Proper identification of the attribute is very important because all the identified attribute will define whole ultrasonic machining system and if it is done carefully then selection of ultrasonic machining system will become very precise and easy. So process of identification of attribute should be highly exhaustive in nature.

TOOL

1) Tool shape
2) Tool size
3) Single or Multiple tool
4) Tool length/diameter
5) Tool rotation (if exist)
6) Type of tool (*Solid /Hollow*)

ABRASIVE

7) Type of Abrasive
8) Abrasive shape
9) Abrasive size

SLURRY

10) Liquid medium
11) Concentration of abrasive in slurry
12) Slurry tank
13) Slurry pump
14) Viscosity
15) Temperature
16) Feeding mechanism
17) Pressure

DATA ACQUISITION SYSTEM

18) Feed control panel
19) Dynamometer
20) A/D Converter
21) Amplifier

22) Fixture

23) Work piece

- **i.** Type of material
- **ii.** Thickness of work piece
- **iii.** Hardness of work piece
- **iv.** Strength of work piece

COOLANT SYSTEM

24) Coolant tank

25) Pump

26) Flow rate gauge

27) Pressure regulator

28) Valve

29) Pressure gauge

PROCESS PARAMETERS

30) Frequency

31) Amplitude

32) Static loading

33) Hardness ratio of tool and work piece

PERFORMANCE

34) Material removal rate

35) Surface roughness

36) Tool wear rate

37) Machining time

38) Cutting force

39) Form geometric

40) Dimensional accuracy

TOOL HOLDER

41) Material

42) Shape

INPUT PARAMETERS

43) Abrasive slurry types

44) Acoustic head

45) Body with work table

46) Feed

47) Horn

- **i.** Exponential
- **ii.** Tapered
- **iii.** Stepped

48) Generator
49) Coolant
50) Transducer
i. Piezoelectric
ii. Magnetostrictive

4.3.1 Types of Parameter:- The parameters listed above has been divided into Qualitative and Quantitative parameters

Quantitative Parameters:- These parameters are also called deterministic parameters as these parameters can be given the value. Ultrasonic machining system can be rated on the scale 1-4. The Ratings have been done based on the Cause and effect diagram of the performance parameters i.e. MRR, TWR and Surface Roughness. If the parameter affects all the three performance parameter it is rated 4. If the Parameter effects any two performance parameter out of three performance parameter then it is rated 3 likewise so on.

Qualitative Parameters: - All the parameter are not quantitative. The qualitative parameters are non deterministic in nature.These parameters are also called subjective or fuzzy parameters. As all the parameters cannot be given the value so these parameters have been categorized as qualitative parameters based on whether the parameter is used in the machine or not. If the parameter is used in the machine then it is coded as Y and if the parameter is not used in the machine then it is coded as N.

4.3.1(a)Usefulness to the manufacturer

The quantification and monitoring of the parameter magnitudes will help the manufacturer to control them closely so that he can fulfil the demand of the user precisely. Moreover, he can find out the market fashion by observing the parameter magnitudes. This will help the manufacturer to modify the ultrasonic machining system to suit the future needs of the ultrasonic machine user. He can use the information to produce the optimum results in the minimum possible time. He can also use these parameters for the SWOT (Strength- Weakness- Opportunity-Threat) analysis of his product.

4.3.1(b)Usefulness to the researcher

This identification of the parameters will help the researcher for the database storage and its retrieval. This will generate the programmed database, which can be used in different formats by different people for different purposes in the organization. The researcher will know what are the physical characteristics and performance parameters of the ultrasonic machining system.

4.3.1(c) Usefulness to the designer

He can identify the critical parameters, which directly affects the performance parameters by the use of cause and effect analysis. The designer can change these critical parameters and monitor them to obtain required performance parameter value from the ultrasonic machining system.

Coding Scheme:- After identification of the parameters, the parameters are coded either numerically or alphabetically on the basis of cause and effect diagram. This is done under coding scheme which is very important as it gives detailed information about parameters.The coding is done for storing data in computer which will help the manufacturers , designers, researchers in better understanding .The cause and effect diagram is made so as to find out which parameter affect the performance parameter and which parameter does not affects performance parameters.

4.4 Coding for parameters affecting performance

DESCRIPTION	**CODING**	
IF THE PROCESS PARAMETER EFFECT ALL THE THREE PERFORMANCE PARAMETER	VERY MUCH EFFECTIVE	*4*
IF THE PROCESS PARAMETER EFFECT TWO OF THE THREE PERFORMANCE PARAMETER	VERY EFFECTIVE	3
IF THE PROCESS PARAMETER EFFECT ANY ONE PERFORMANCE PARAMETER OUT OF THREE PERFORMANCE PARAMETERS	EFFECTIVE	2

IF THE PROCESS PARAMETER DOESN'T EFFECT ANY OF THE PERFORMANCE PARAMETER	NOT EFFECTIVE	1
IF PARAMETER IS NOT KNOWN	-	0
IF THE PARAMETER IS USED IN THE MACHINE	YES USED	Y
	NOT USED	N

CAUSE AND EFFECT DIAGRAM

There are seven performance parameter but concentration is made to improve three performance parameters i.e. Material Removal Rate , Tool Wear Rate, Surface Roughness and cause and effect diagram are used to find out parameters that affects the performance parameters. The cause and effect diagram is also called Ishikawa diagram, Fishbone diagram. It graphically illustrates relationship between a given outcome and all the factors that affect the outcome. A cause and effect diagram is useful for identifying and organizing the known or possible causes of performance parameters. Cause and Effect Diagram is drawn to

- Determine the root causes of performance parameter using structured approach.
- Indicate possible causes of variation in ultrasonic machining system.
- Increase the knowledge of the ultrasonic machining process by helping everyone to learn more about the factors at work and how they relate.
- Indentify areas for collecting data.

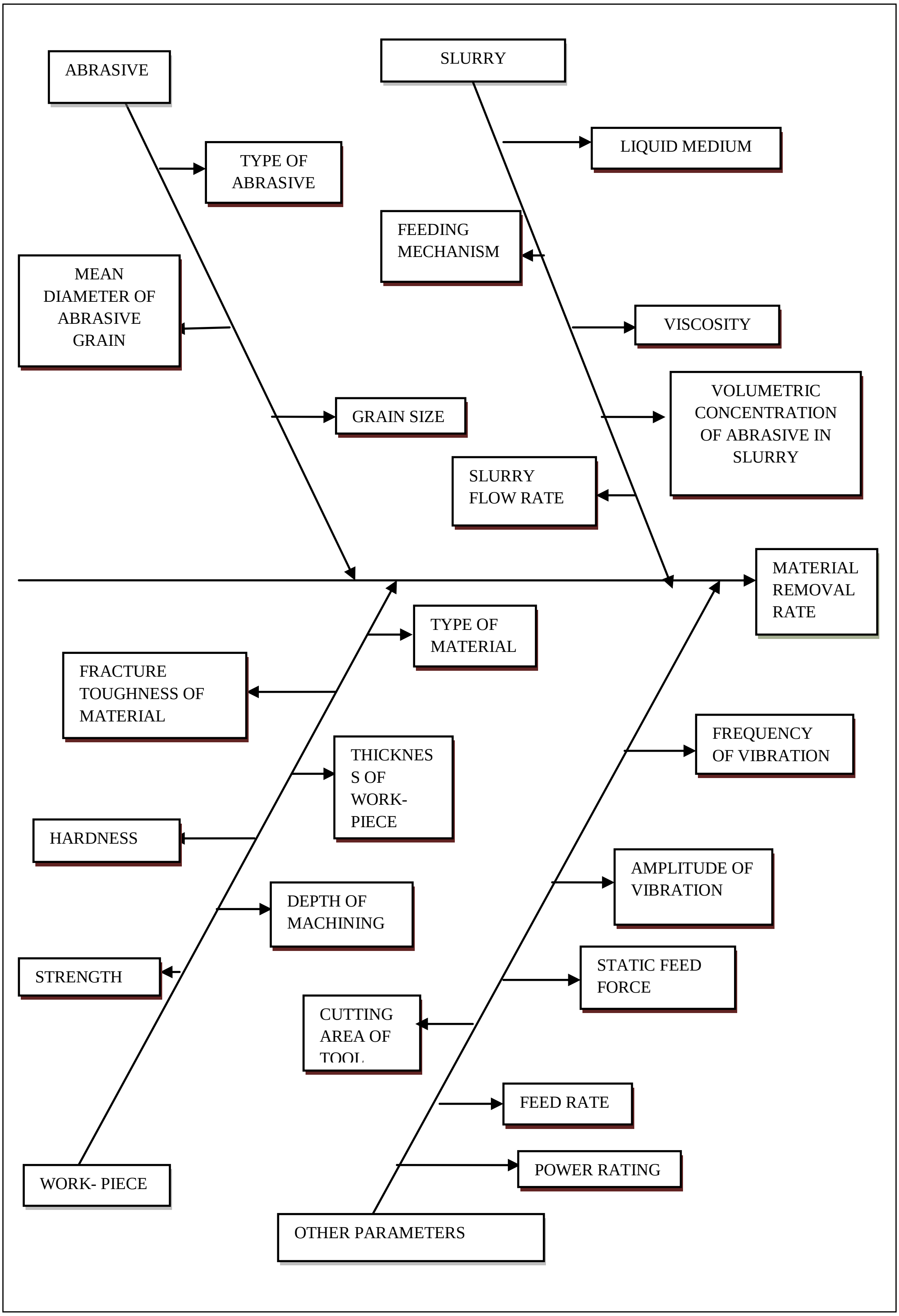


Fig.4.1 Cause and Effect diagram of MRR

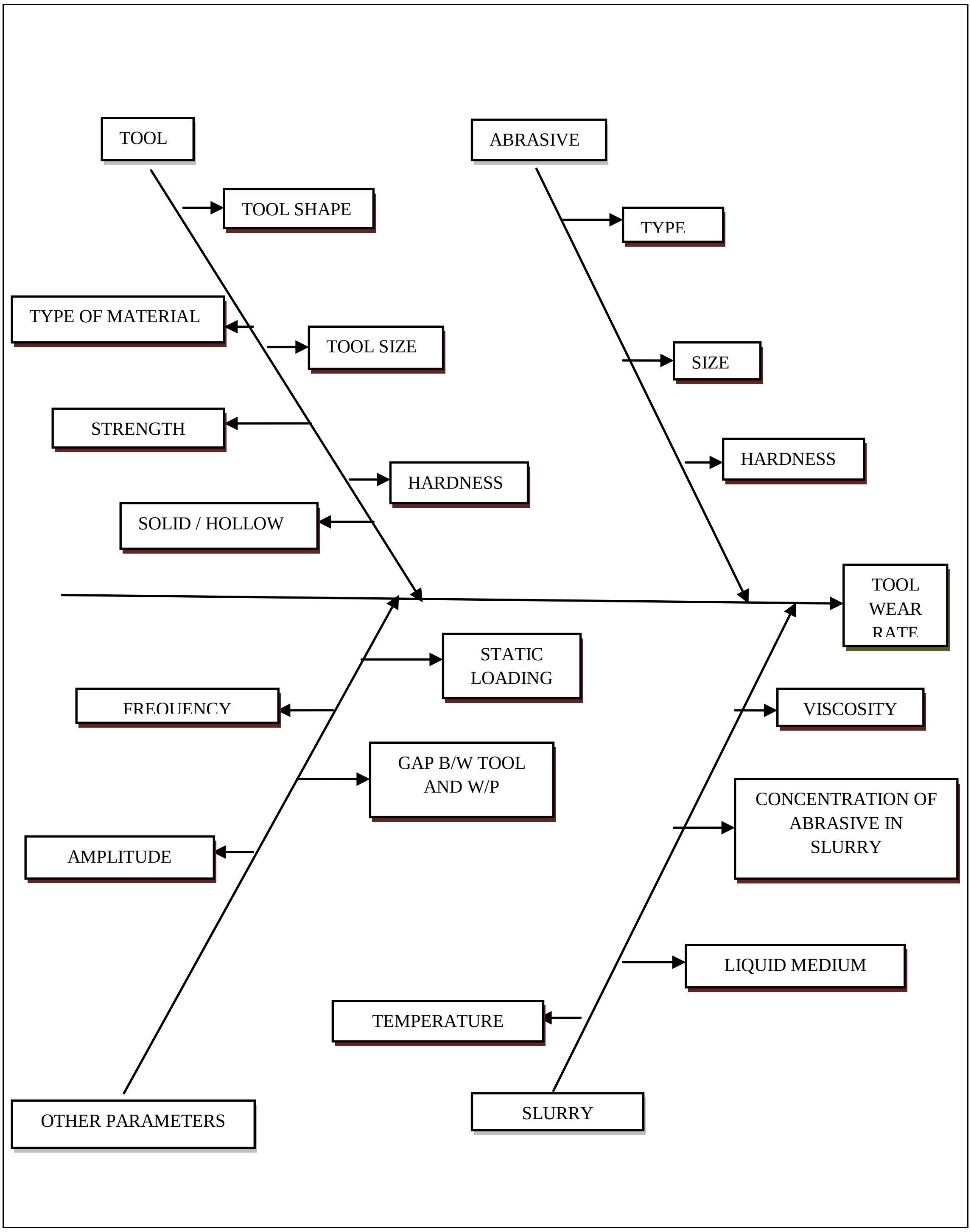


Fig 4.2. Cause and Effect diagram of TWR

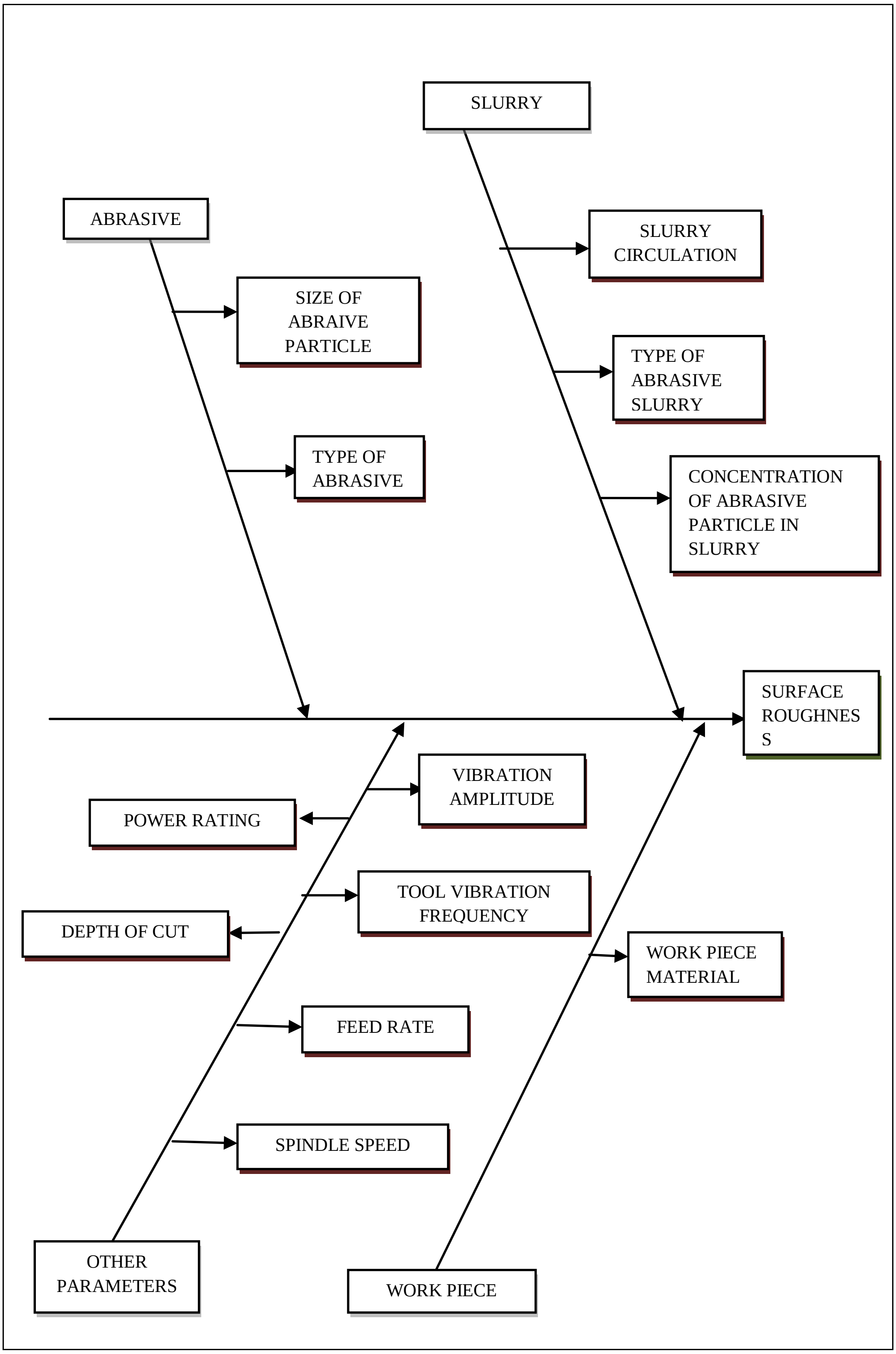


Fig. 4.3 Cause and Effect diagram of Surface Roughness

Table 4.1

Ultrasonic Machining identification coding scheme

Tool	1	2	3	4	5	6			
Abrasive	7	8	9						
Slurry	10	11	12	13	14	15	16	17	
Data Acquisition system	18	19	20	21	22	23(i)	23(ii)	23(iii)	23(iv)
Coolant system	24	25	26	27	28	29			
Process parameters	30	31	32	33					
Performance	34	35	36	37	38	39	40		
Tool Holder	41	42							
Input parameters	43	44	45	46	47	48	49	50	

The above table represents a 50-digit code /nomenclature for the ultrasonic machining system. The user can give codes to these parameters according to his needs before using this coding system. To illustrate coding procedure, coding scheme of the Sonic Mill ultrasonic machine is developed as shown in Table 2.

Table 4. 2

Example: Sonic Mill Ultrasonic Machining

Sr. No	Attribute	Information	Code
1	Tool shape	-	2
2	Tool size	-	2
3	Single or Multiple tool	-	1
4	Tool length/ diameter	-	1
5	Tool rotation (if	-	1

	exist)		
6	Type of tool	-	2
7	Type of Abrasive	-	4
8	Abrasive shape	-	2
9	Abrasive size	-	4
10	Liquid medium	-	2
11	Concentration of abrasive in slurry	-	4
12	Slurry tank	-	Y
13	Slurry pump	-	Y
14	Viscosity	-	2
15	Temperature	-	1
16	Feeding mechanism	-	2
17	Pressure	-	1
18	Feed control panel	-	N
19	Dynamometer	-	N
20	A/D Converter	-	N
21	Amplifier	-	N
22	Fixture	-	N
23(i)	Type of work piece material	-	3
23(ii)	Thickness of work piece	-	2
23(iii)	Hardness of work piece	-	2
23(iv)	Strength of work piece	-	2
24	Coolant tank	-	N
25	Coolant pump	-	N
26	Flow rate gauge	-	N
27	Pressure regulator	-	N
28	Valve	-	N
29	Pressure gauge	-	N

30	Frequency	-	4
31	Amplitude	-	4
32	Static loading	-	3
33	Hardness ratio of tool and work piece	-	3
34	Material removal rate	-	0
35	Surface roughness	-	0
36	Tool wear rate	-	0
37	Machining time	-	0
38	Cutting force	-	0
39	Form geometric	-	0
40	Dimensional accuracy	-	0
41	Material of tool holder	-	1
42	Shape of tool holder	-	1
43	Abrasive slurry types	-	3
44	Acoustic head	-	N
45	Body with work table	-	Y
46	Feed	-	2
47	Horn	Tapered	T
48	Generator	-	Y
49	Coolant	-	N
50	Transducer	Piezoelectric	P

Table 4.3

Ultrasonic machining identification code

Tool	2	2	1	1	1	2			
Abrasive	4	2	4						
Slurry	2	4	Y	Y	2	1	2	1	

Data Acquisition system	N	N	N	N	N	3	2	2	2
Coolant system	N	N	N	N	N	N			
Process parameters	4	4	3	3					
Performance	0	0	0	0	0	0	0		
Tool holder	1	1							
Input parameters	3	N	Y	2	T	Y	N	P	

These codes are useful in documenting available parameters for storing, retrieving and manipulating a database during evaluation and selection of an optimum parameter from a large number of parameters. 0 represent the parameters about which information is not available to the user.

4.5 The 3 stage selection procedure

Selection procedure :- The selection of best possible ultrasonic machining system from the alternatives available in global market for a given application is extremely important. The main emphasis is to select a USM system which is cheap and effective for use in different applications and hence is cost efficient. So after consideration and evaluation of all parameters best USM system suited for particular area and application is selected. The selection procedure consists of 3 stages

1) Elimination search
2) Evaluation , Comparison , Ranking and optimum Selection using Attribute
3) Final Selection by decision makers by using SWOT analysis

4.5.1 1st stage Elimination search

All the parameters identified, would not be important while selection of ultrasonic machining system. There will be few parameters which have a direct effect on the selection procedure. This small number of parameters may be set as ‘pertinent parameters’ as necessitated by the user. If we take all the parameter then it will be cost effective and time consuming so we are reducing parameters to pertinent parameters. Hence the selection procedure focuses only on the relevant parameters leaving out the rest parameters.

4.5.2 2nd stage Evaluation , Comparision ,Ranking and Optimum Selection using Attribute

1) First step is to make matrix called decision matrix D .Each row of this matrix corresponds to alternate of ultrasonic machining system and each column corresponds to parameter of ultrasonic machining system. An element d_{ij} of this matrix corresponds to the value of j^{th} parameter for i^{th} alternate of ultrasonic machining system. Row represents alternates of ultrasonic machining system whereas column represents the parameters of ultrasonic machining system. Thus if the number of alternate of ultrasonic machining system taken to be ‘m’ and a number of parameters of ultrasonic machining system is ‘n’, the decision matrix is “m * n” matrix. This matrix is also called database matrix or Information matrix or knowledge base matrix.

$$D = \begin{bmatrix} d_{11} & d_{12} & d_{13} & \cdots & d_{1n} \\ d_{21} & d_{22} & d_{23} & \cdots & d_{2n} \\ d_{31} & d_{32} & d_{33} & \cdots & d_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ d_{m1} & d_{m2} & d_{m3} & \cdots & d_{mn} \end{bmatrix}$$

2) The normalized specification matrix will have the values of all parameters of the alternate of ultrasonic machining system from 0 to 1. It is a sort of value , which indicates the magnitude of particular parameter of ultrasonic machining system compared to a whole range of the magnitudes of all alternates of ultrasonic machining system for that particular parameter of ultrasonic machining system. This matrix is calculated as

$$n_{ij} = \frac{d_{ij}}{\sqrt{\sum_{i=1}^{m} (d_{ij})^2}}$$

Where d_{ij} = element of decision matrix D.

It provide the dimensionless magnitudes

3) The relative importance matrix A is obtained from a group of experts. This matrix will give relative importance of one parameter of ultrasonic machining system over other parameter. The relative importance matrix is represented by A= $[a_{ij}]$. Here a_{ij} represents relative importance of i^{th} parameter of ultrasonic machining system over j^{th} parameter of ultrasonic machining system. This is n*n matrix. The information is based on pairwise comparison.

4) The Eigenvector method, allows for some inconsistencies in the judgment of relative importance of parameter of ultrasonic machining system while making pair- wise comparisons' used to find weights. The Eigenvector w is taken to correspond to the largest Eigenvalue λ_{max} and this is calculated as

$$(A-\lambda_{max}I)=0$$

And weights be measured as

$$[A-\lambda_{max}I][w]=0$$

$$\text{And } \sum_{i=1}^{n} w_i = 1$$

5) Weighted Normalized Matrix , V is calculated by multiplying weights of parameters of ultrasonic machining system by Normalized matrix ,N

$$V = \begin{bmatrix} w_1n_{11} & w_2n_{12} & w_3n_{13} & \cdots & w_nn_{1n} \\ w_1n_{21} & w_2n_{22} & w_3n_{23} & \cdots & w_nn_{2n} \\ w_1n_{31} & w_2n_{32} & w_3n_{33} & \cdots & w_nn_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ w_1n_{m1} & w_2n_{m2} & w_3n_{m3} & \cdots & w_nn_{mn} \end{bmatrix} = \begin{bmatrix} v_{11} & v_{12} & v_{13} & \cdots & v_{1n} \\ v_{21} & v_{22} & v_{23} & \cdots & v_{2n} \\ v_{31} & v_{32} & v_{33} & \cdots & v_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ v_{m1} & v_{m2} & v_{m3} & \cdots & v_{mn} \end{bmatrix}$$

It will give the right comparable values of the parameters of ultrasonic machining system.

6)Ranking and selection Procedure

TOPSIS Method:- The TOPSIS method is based on the concept that selected ultrasonic machining system should have the shortest Euclidean distance from the ideal solution, and the extreme from the negative ideal solution. The ideal solution is an imaginary solution for which all the parameter values of ultrasonic machining system correspond to the maximum parameter value in the database comprising the satisfying solutions; the negative- ideal solution is the imaginary solution for which all parameter values of ultrasonic machining system correspond to the minimum parameter value in the database. The weighted normalized matrix V is used to obtain the best alternate and the worst possible alternate of the ultrasonic machining system.

$v_i^* = \{[\overset{max}{_{j=1;i=1,m}} v(i,j)], [\overset{max}{_{j=2;i=1,m}} v(i,j)], \ldots\ldots [\overset{max}{_{j=n;i=1,m}} v(i,j)]\}$

$v_i^- = \{[\overset{min}{_{j=1;i=1,m}} v(i,j)], [\overset{min}{_{j=2;i=1,m}} v(i,j)], \ldots\ldots [\overset{min}{_{j=n;i=1,m}} v(i,j)]$

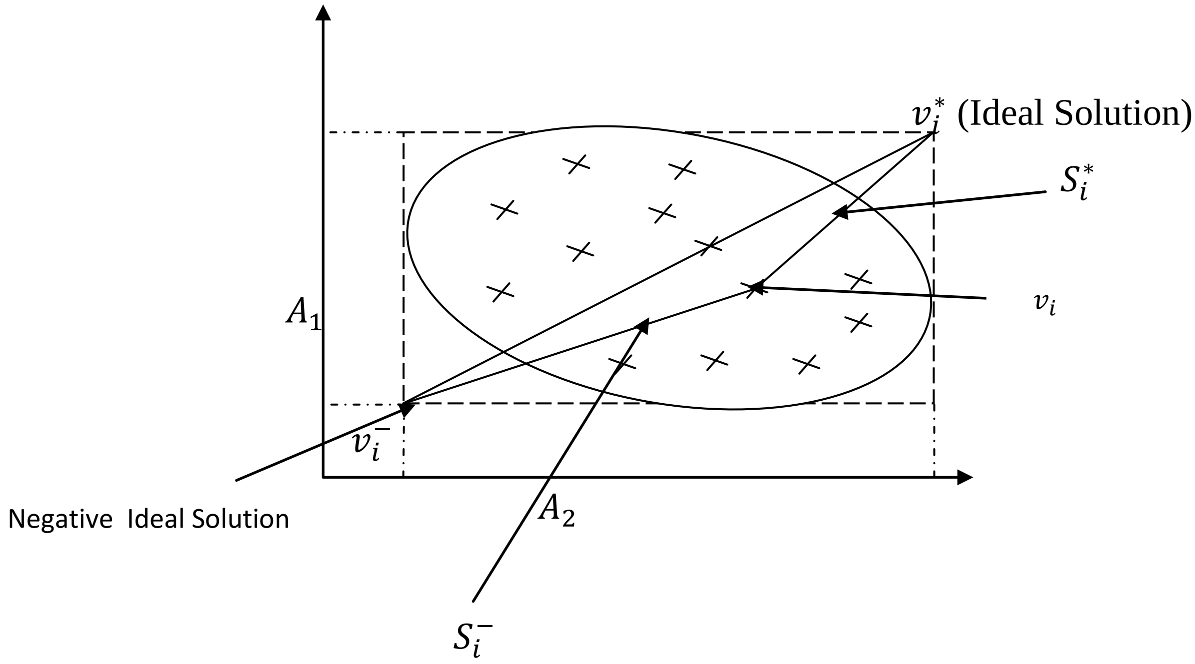


Fig. 4.4 Representation of the selection problem in case of two attribute (A_1 and A_2) for the 2-D case

The separation for best possible alternate of ultrasonic machining system is given by

$S_i^* = [\sum_{j=1}^{n}(v_{ij}\text{-}v_i^*)^2]^{1/2}$

And separation for worst possible alternate of ultrasonic machining system is given by

$S_i^- = [\sum_{j=1}^{n}(v_{ij}\text{-}\ v_i^-)^2]^{1/2}$

Where

S_i^* = separation from ideal solution measured by the n- dimensional Euclidean distance between the i^{th} ultrasonic machining system and the ideal solution.

S_i^- = separation from the negative – ideal solution measured by the n-dimensional Euclidean distance between the i^{th} ultrasonic machining system and negative – ideal solution .

n-dimensional attribute space (Hyperspace) :- Graphical representation for n-dimensional attribute space can not be drawn. Graphical representation can be drawn for 2-dimensional feature space and 3-dimensional feature space.

6) TOPSIS considers the distance to both the ideal and negative ideal solution by defining 'relative closeness to the finest result'. The relative closeness to the best possible ultrasonic machining system $C_i{}^*$ is calculated as

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^*}$$

The ultrasonic machining system with largest C_i^* is preferred

4.5.3 3rd step Final Selection by decision makers by using SWOT analysis

We are proposing SWOT analysis for identifying Strengths, Weakness, Oppurtunity and Threats in research work.

Strengths :- It gives advantages of Ultrasonic Machining Process over other methods.

Weakness:- It gives limitation of Ultrasonic Machining Process over other methods.

Oppurtunity :- These are external chances to improve the ultrasonic machining

Threats :- These are the problem that may occur in ultrasonic machining process and can be removed by other used methods.

Table 4.4 :- SWOT Analysis of Ultrasonic Machine

STRENGTH	WEAKNESS
1) Can Drill circular or non circular holes in a very rigid material. 2) Less or no residual stress because of its non thermal characteristics. 3) Protection of work piece and tool because of reduced contact forces and low thermal stress 4) USM is suitable for machining hard and brittle material 5) Machining any materials	1) Low material removal rate[48]. 2) Tool wears fast in USM[48] 3) Machining area and depth is restrained in USM [48]

regardless of their conductivity. 6) With Bullen's unique ultrasonic machining technology , the chemical and physical property of your substrate material remain unchanged , increasing reliability.[54]	
OPPURTUNITY	**THREATS**
1) Dimensional exactness[54] 2) Improve your production yield.[54] 3) Increase the reliability of your design[54] 4) Reduce your total solution cost[54] 5) USM can be used to generate wide range of intricate features in advanced material.	1) RUM is a convenient and inexpensive way of machining hard and brittle materials.[55] 2) RUM is capable of machining ten times faster than USM under similar conditions.[55] 3) A fine surface finish and a low tool pressure could be achieved as compared to USM [55] 4) RUM is essential for machining micro parts and micro features in hard and brittle materials [55]

4.6 Graphical Methods:- For better understanding of ultrasonic machining system physically, we are proposing Graphical Methods. The mathematical representation of the specifications , normalized and weighted normalized specifications has been discussed above to evaluate ultrasonic machining system. But ultrasonic machining system can also be evaluated graphically. There are two methods to evaluate ultrasonic machining system graphically i.e. Line Graph and Spider Diagram.

4.6.1 Line Representation: - It is the line graph plotted between alternate and parameter of ultrasonic machining system. This graph is plotted on the basis of value used in decision matrix, normalized matrix and weighted normalized matrix. This graph is different for all ultrasonic machining system and comparison can be made by calculating area under graph.

Area under the line graph of order of i^{th} Ultrasonic machining system can be calculated as

$AD_i^L = (d_{i,1} + 2(d_{i,2} + \ldots\ldots\ldots + d_{i,n-1}) + d_{i,n})/2$

Similarly, area under graph of normalized and weighted normalized specifications of the i^{th} Ultrasonic machining system i.e. AN_i^L and AV_i^L can be calculated using their respective elements.

The system with least value of area under curve is ranked last whereas system with highest value of area under curve is ranked first i.e. Higher area under curve is preferable.

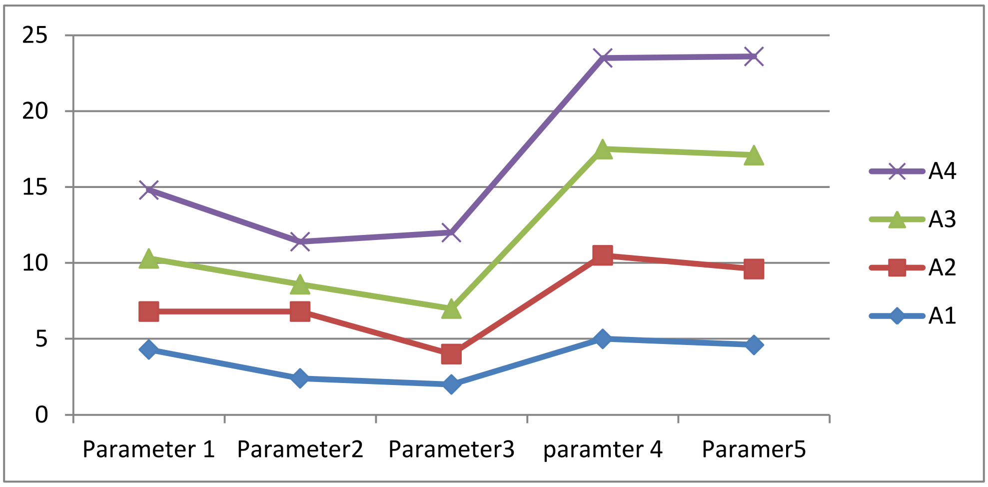


Fig. 4.5 Line Graph plot for the specifications and area under graph is shaded

Where A1, A2, A3 and A4 represents four alternates.

4.6.2Spider Diagram: - It is polygon diagram with number of sides equal to the number of parameters of ultrasonic machining system and area enclosed by graph is shown by alternates of ultrasonic machining system. The angle θ between the parameter axis can be calculated as θ = 2π/n where n represents number of parameters of ultrasonic machining system taken under consideration. It is also known as polar or radar diagram.

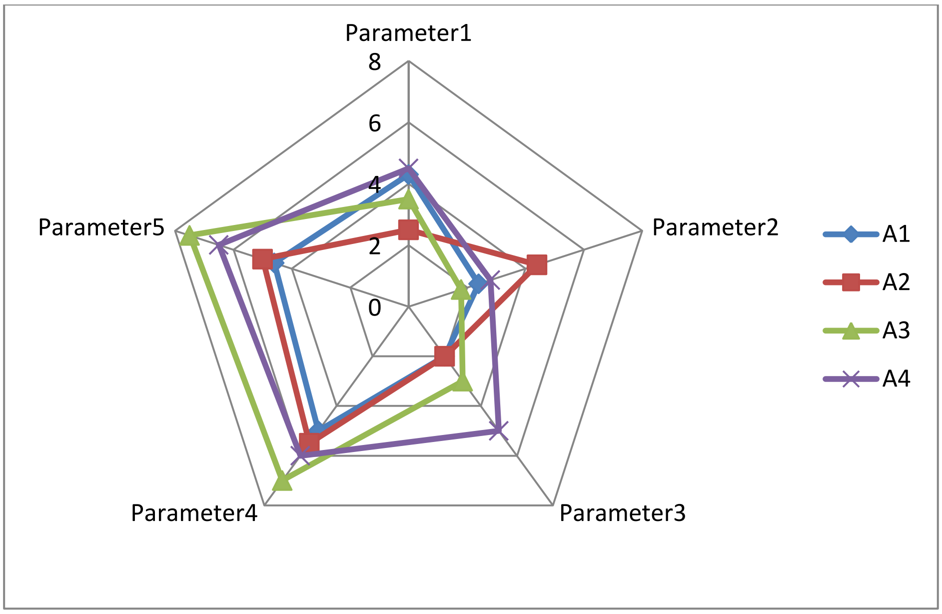


Fig.4.6 Spider Diagram Polygon for the specifications and the area enclosed is shaded

Let d_{ij} represents the value of j^{th} parameter in the i^{th} alternate of ultrasonic machining system along θ_i

Let n_{ij} represents the normalized value of j^{th} parameter in the i^{th} alternate of ultrasonic machining system along θ_i

Let v_{ij} represents the weighted normalized value of j^{th} parameter in the i^{th} alternate of ultrasonic machining system along θ_i

$$AD_i^S = \frac{\sin\theta}{2} \sum_{j=1}^{n} d_{ij} d_{i,j+1} \text{ where } d_{i,n+1} = d_{i,1}$$

Similarly area enclosed by polygon for normalized and weighted normalized specifications of ultrasonic machining system i.e. AN_i^S and AV_i^S respectively are calculated.

4.6.3 Identification and Graphical Representation of the benchmark USM

For the comparison of ultrasonic machining system for grade purpose +ve benchmark ultrasonic machining system is defined. The areas under line graph for +ve benchmark ultrasonic machining system i.e. AD_B^L , AN_B^L , AV_B^L are calculated. The area enclosed by the polygon of radar diagram for +ve benchmark ultrasonic machining system i.e. AD_B^R, AN_B^R, AV_B^R are calculated . All the ultrasonic machining system will be compared with +ve benchmark ultrasonic machining system for evaluation purpose.

4.6.4 Ranking and Selection of Ultrasonic Machining System

We have decision matrix , normalized matrix and weighted normalized matrix ready for all ultrasonic machining system along with +ve benchmark ultrasonic machining system. Comparison is made between ultrasonic machining system with +ve benchmark ultrasonic machining system so that they can be ranked and selected.

Coefficient of Similarity (COS):- Let Coefficient of Similarity be the ratio of area enclosed by the polygon for the ultrasonic machining system to the area enclosed by the polygon for +ve benchmark ultrasonic machining system. The value of COS lies between 0and 1 i.e. ($0 \leq COS \leq 1$). It measures closeness of ultrasonic machining system with +ve benchmark ultrasonic machining system. The ultrasonic machining system with COS magnitude closer to unity is preferable, since it indicates closeness to +ve benchmark ultrasonic machining system.

Coefficient of Similarity (COS) based on decision matrix

$COS_i^D = AD_i / AD_B$

Where AD_i Area of i^{th} ultrasonic machining system in decision matrix in Line Graph method and Spider Diagram method.

Coefficient of Similarity (COS) based on the normalized specification matrix

$COS_i^N = AN_i / AN_B$

Where AN_i Area of i^{th} ultrasonic machining system in normalizedspecification matrix in Line Graph method and Spider Diagram method.

Coefficient of Similarity (COS) based on the weighted normalized specification matrix in Line Graph method and Spider Diagram method.

$COS_i^V = AV_i / AV_B$

Where AV_i Area of i^{th} ultrasonic machining system in Weighted Normalized matix in Line Graph method and Spider Diagram Method

Examples

Illustrative example 4.1:-

The values used in the decision matrix has been taken from the literature [46]

Work piece

1. **1.)** Tungsten carbide (WC)
2. **2.)** Stealite (St)
3. **3.)** Poly crystalline diamond (PCD)

Tool :- TITAN 12

Abrasive = Alumina (Al_2O_3)

Slurry Concentration = 20%

Abrasive grit size = 220

Power rating = 25% of 500W= 125W

4.1.1 TOPSIS method

Step 1. Formation of Decision matrix , 'D' , i.e. matrix will contain all magnitudes of specifications. The rows of matrix represents the type of work piece material i.e. Tungsten carbide (WC),Stealite (St) and Poly crystalline diamond (PCD) and column represents performance parameters i.e. MRR, TWR and Surface Roughness

$$D=\begin{bmatrix} 25.589 & 17.887 & 16.569 \\ 26.634 & 17.887 & 26.235 \\ 31.588 & 5.644 & 15.660 \end{bmatrix}$$

Step 2. Calculating the normalized specification matrix. This normalization helps to give the dimensionless elements of the matrix in the 0-1 range. Normalized specification matrix of i^{th} work piece calculated is shown below in the (4.1)

$$n_{i,j} = \frac{d_{ij}}{\sqrt{\sum_{i=1}^{m} d_{ij}^2}}$$

$$N = \begin{bmatrix} 0.5265 & 0.6901 & 0.4767 \\ 0.5480 & 0.6901 & 0.7548 \\ 0.6499 & 0.2178 & 0.4506 \end{bmatrix} \quad (4.1)$$

Step 3. Construction of Relative importance matrix A.

A group of expert will establish the relative importance of the performace parameters i.e. MRR,TWR and Surface Roughness with respect to each other.

$$A = \begin{bmatrix} & MRR & TWR & Surface\ Roughness \\ MRR & 1 & 9 & 3 \\ TWR & 1/9 & 1 & 1/5 \\ Surface\ Roughness & 1/3 & 5 & 1 \end{bmatrix}$$

Step 4. Finding out the maximum Eigen value of the relative importance matrix A. Eigen value can be calculated from the as equation (4.2).

$$(A-\lambda I) = \begin{bmatrix} 1-\lambda & 9 & 3 \\ 1/9 & 1-\lambda & 1/5 \\ 1/3 & 5 & 1-\lambda \end{bmatrix}$$

$(A-\lambda I)=0$

$-\lambda^3 + 3\lambda^2 + 0\lambda + 4/15 = 0 \quad (4.2)$

From above equation we get

$\lambda = 3.0291$, $-0.0145+0.2964i$, $-0.0145 - 0.2964i$

$\lambda_{max} = 3.0291$

Weights are calculated for each Performace parameter using the Eigenvector associated with a maximum Eigen value by using equations (4.3) and (4.4).

$[A-\lambda_{max}I][w] = 0$

And $\sum_{j=1}^{n} w_j = 1$

$$\begin{bmatrix} -2.0291 & 9 & 3 \\ 1/9 & -2.0291 & 1/5 \\ 1/3 & 5 & -2.0291 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} = 0 \quad (4.3)$$

And $w_1 + w_2 + w_3 = 1 \quad (4.4)$

From here we get

w_1 = 0.67179681

w_2= 0.062937217

w_3= 0.265446927

Step 5. Calculating the weighted normalized specification matrix. This matrix is calculated by multiplying weights of respective performance parameter by normalized specification matrix.

$$V = \begin{bmatrix} 0.3537 & 0.0434 & 0.1265 \\ 0.3681 & 0.0434 & 0.2004 \\ 0.4366 & 0.0137 & 0.1196 \end{bmatrix}$$

This weighted normalized specification matrix is all- inclusive matrix, which takes care of the parameter values and their relative importance.

Step 6. TOPSIS method for ranking

The Weighted normalized parameter for the best and worst work piece can be obtained.

Next we determine the ideal solution v_i^* and the negative ideal solution v_i^- by choosing from V matrix the maximum and minimum values of the Performace parameter as shown below in the equations (4.5) and (4.6)

$$v_i^* =\{[\max_{j=1;i=1,m} v(i,j)], [\max_{j=2;i=1,m} v(i,j)], \ldots\ldots [\max_{j=n;i=1,m} v(i,j)]\}$$

$$v_i^- = \{[\min_{j=1;i=1,m} v(i,j)], [\min_{j=2;i=1,m} v(i,j)], \ldots\ldots [\min_{j=n;i=1,m} v(i,j)]\}$$

V_i^*= (0.4366, 0.0434, 0.2004) (4.5)

V^-_i = (0.3537,0.0137,0.1196) (4.6)

Then we calculate separation measures of each alternative i.e. work piece from v_i^* and v_i^-

The separation from ideal solution measured by the n- dimensional Euclidean distance between the i^{th} Work piece and the ideal solution can be calculated as shown below in the equation (4.7).

$$S_b = [\sum_{j=1}^{n}(v_{ij}-v_i^*)^2]^{1/2} \quad (4.7)$$

The separation from negative ideal solution measured by the n- dimensional Euclidean distance between the i^{th} Work piece and the negative ideal solution can be calculated as shown below in the equation (4.8)

$$S_n =[\sum_{j=1}^{n}(v_{ij}- v_i^-)^2]^{1/2} \quad (4.8)$$

$S_1^* = 0.1110$ $S_1^- = 0.0305$

$S_2^* = 0.0685$ $S_2^- = 0.0872$

$S_3^* = 0.0860$ $S_3^- = 0.0829$

Step 7:- Relative closeness to the ideal solution of i^{th} Work piece can be calculated as shown below in the equation (4.9)

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^*} \qquad (4.9)$$

$C_1^* = 0.2155477032$

$C_2^* = 0.5600513809$

$C_3^* = 0.4908229722$

Table 4.5 :- Ranking of work piece in Ascending Order on the basis of TOPSIS method

Sr.No.	Relative Closeness to Ideal Solution	Value
1	C_2^*	0.5601
2	C_3^*	0.4908
3	C_1^*	0.2155

As the value of C_2 is highest so Stellite is best work piece and As value of C_1 is lowest so Tungsten Carbide is worst work piece on the basis of TOPSIS method.

4.1.2Line Diagram:-

$$V = \begin{bmatrix} 35.37 & 2.17 & 4.22 \\ 36.81 & 2.17 & 6.68 \\ 43.66 & 0.685 & 3.99 \end{bmatrix}$$

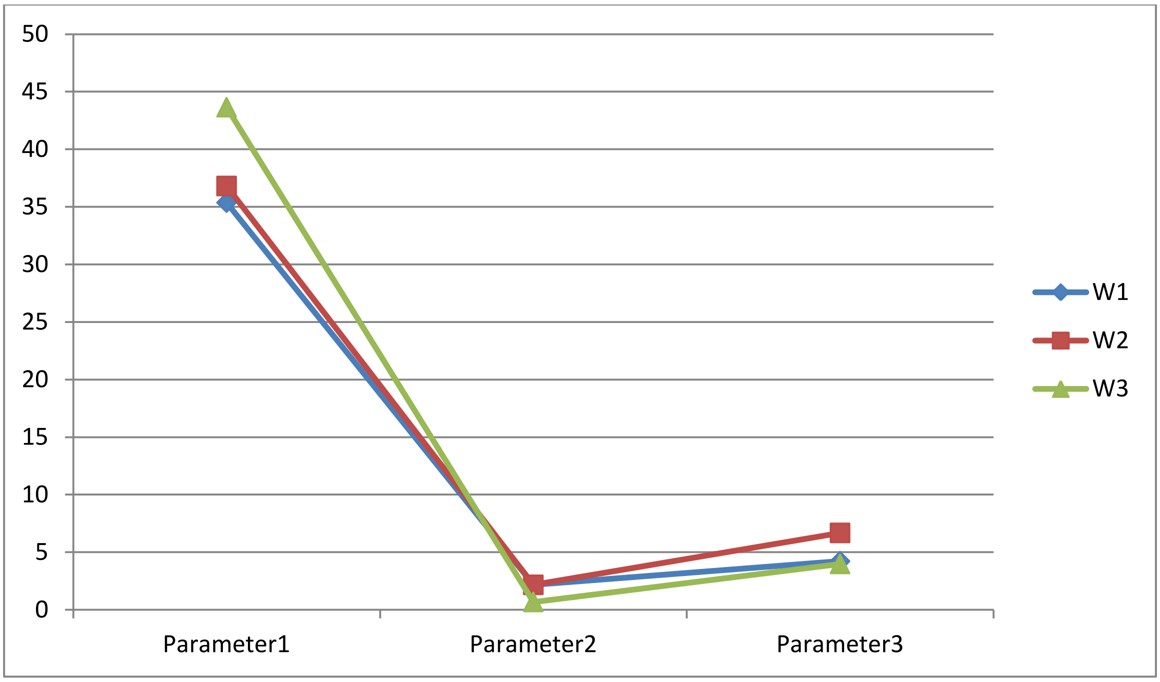


Fig. 4.7 Line graph plot for the specifications of work piece

In Fig.4.7 W_1, W_2, W_3 represents Tungsten Carbide (WC), Stellite and Polycrystalline Diamond (PCD) respectively . whereas Parameter1 ,Parameter2, Parameter3 corresponds to MRR, TWR and Surface Roughness respectively.

Step1: - Area under the line graph of order of i^{th} Work piece can be calculated as shown below in the equation (4.10)

$$AV_i^L = [v_{i,1} + 2(v_{i,2} + \ldots\ldots\ldots\ldots\ldots + v_{i,n-1}) + v_{1,n}] /2 \quad (4.10)$$

AV_1^L = [35.37 + 2(2.17) + 4.22]/2 = 21.965

AV_2^L = [36.81 + 2(2.17) + 6.68]/2 = 23.915

AV_3^L = [43.66 + 2(0.685) +3.99] /2 = 24.51

Step2 :- Identification of Benchmark Work piece

The highest area out of three area calculated above is taken as benchmark work piece i.e. AV_3^L

$AV_B^L = AV_3^L$= 24.51

Step3:- Coefficient of Similarity (COS) based on the weighted normalized specification matrix of work piece in Line Graph method is given in the equation (4.11) :-

$$COS_i^{VL} = AV_i^L / AV_B^L \quad (4.11)$$

Where AV_i^L Area of i^{th} Work piece in Weighted Normalized matix in Line Graph method

AndAV_B^L Area of benchmark Work piece in Weighted Normalized matrix in Line Graph method

COS_1^{VL} = 21.965/24.51 = 0.8962

COS_2^{VL} = 23.915/24.51 = 0.9757

COS_3^{VL} = 24.51/24.51 = 1

Table 4.6 :-Ranking of work piece in Ascending order on the basis of Line Graph

Sr.No	COS_i^{VL}	**Value**
1	COS_3^{VL}	1
2	COS_2^{VL}	0.9757
3	COS_1^{VL}	0.8962

As in line diagram value of COS_3^{VL} is highest so Polycrystalline Diamond (PCD) is best work piece. And as value of COS_1^{VL} is lowest so Tungsten Carbide is best work piece.

4.1.3 Spider Diagram

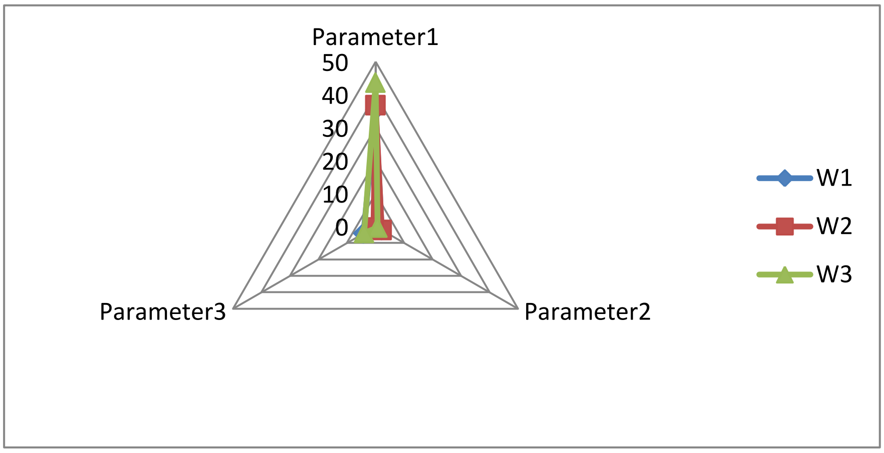


Fig. 4.8 Spider diagram polygon plot for the specifications of work piece and the area enclosed is shaded

In Fig. 4.8 W1,W2,W3 represents tungsten carbide (WC), Stellite (St) and Polycrystalline Diamond (PCD) respectively whereas Parameter1 ,Parameter2, Parameter3 corresponds to MRR, TWR and Surface Roughness respectively.

Step1: - Area under the Spider diagram of order of i^{th} Work piece can be calculated as shown below in the equation (4.12)

$$AV_i^S = \frac{\sin\theta}{2}\left[\sum_{j=1}^{n} v_{i,j}v_{i,j+1}\right] \text{ where } v_{i,n+1} = v_{i,1} \quad (4.12)$$

And θ = 2π/n where θ= angle between parameter axis and n = number of parameters

$\theta = 2\pi/3 = 120°$

$AV_1^S = \frac{\sin 120}{2}$ [(35.37*2.17) + (2.17* 4.22) + (4.22 * 35.37)] = 101.832

$AV_2^S = \frac{\sin 120}{2}$ [(36.81 * 2.17) + (2.17* 6.68) + (6.68* 36.81)] = 147.33

$AV_3^S = \frac{\sin 120}{2}$ [(43.66*0.685) + (0.685* 3.99) +(3.99*43.66)] = 89.56

Step 2:- Identification of Benchmark Work piece

The highest area out of three area calculated above is taken as benchmark work piece i.e. AV_2^S

AV_B^S = AV_2^S = 147.33

Step3:- Coefficient of Similarity (COS) based on the weighted normalized specification matrix of i^{th} work piece in Spider diagram method is given in the equation (4.13) :-

$$COS_i^{VS} = AV_i^S / AV_B^S \quad (4.13)$$

Where AV_i^S Area of i^{th} Work piece in Weighted Normalized matix in Spider diagram method

And AV_B^S Area of benchmark Work piece in Weighted Normalized matrix in Spider Diagram method

COS_1^{VS} = 101.832/147.33 = 0.6912

COS_2^{VS} = 147.33/147.33 =1

COS_3^{VS} = 89.56/147.33=0.6078

Table 4.7 :-Ranking of work piece in Ascending order on the basis of Spider Diagram

Sr.No.	COS_i^{VS}	Value
1	COS_2^{VS}	1
2	COS_1^{VS}	0.6912
3	COS_3^{VS}	0.6078

In spider diagram as the value of COS_2^{VS} is highest so Stellite is best work piece and as the value of COS_3^{VS} is lowest so Polycrystalline Diamond(PCD) is worst work piece

Table 4.8 Evaluation and Ranking of work piece using various methods

Work piece	TOPSIS-closeness to +ve benchmark work piece	Rank based on C^{*}	COS based on Line Graph COS^{VL}	Rank based on COS^{VL}	COS based on Spider Diagram COS^{VS}	Rank based on COS^{VS}
Tungsten Carbide (WC)	0.2155	3	0.8962	3	0.6912	2
Stealite (St)	0.5601	1	0.9757	2	1	1
Polycrystalline diamond (PCD)	0.4908	2	1	1	0.6078	3

Table 4.9 Ranking of work piece based on Comparision of three methods:-

Work piece	Ranking
Stellite	1
Polycrystalline Diamond(PCD)	2
Tungsten Carbide (WC)	3

Role of User in selection

Ranking done by TOPSIS method and two Graphical method vary from each other. Before final decision taken to buy the work piece the following points come into picture (1) Economic Consideration (2) Availability (3) Historical progression (4) Comparative time to Cut steel, which were not previously considered in coding and evaluation . However even if the above consideration , say economic consideration doesn’t allow the user to buy top ranked work piece , the user knows which one to go for the next choice . In this Example as the cost of Stellite is less than the cost of Polycrstalline diamond (PCD) and tungsten carbide (WC) so Stellite is considered to be the best work piece .

Example 4.2:-

The values used in the table are taken from [50]

Table 4.10 Specifications of Ultrasonic Transducer

Sr. No.	TYPE	RESONANCE IMPEDANCE (Ω)	STATIC CAPACITY (pF)	FREQUENCY (kHz)	INPUT POWER (W)
1	BJC-1750D-35HNPZT8	10-20	2550	17	50
2	BJC-2060D-38HNPZT8	10-20	3800	20	60

3	BJC-22100D-45HNPZT8	10-20	5300	22	100
4	BJC-25100D-68HMPZT4	10-20	6700	25	100
5	BJC-28120D-50HMPZT8	10-20	7500	28	120
6	BJC-3360D-38HNPZT8	10-20	3700	33	60
7	BJC-4050D-35HMPZT4	10-20	4100	40	50

4.2.1 TOPSIS method

Step 1:- Formation of Decision matrix , 'D' , i.e. matrix will contain all magnitudes of specifications of ultrasonic transducer. The rows of matrix represent the type of Ultrasonic Transducer and column represent its specification i.e. Static Capacity (pF), Frequency (kHz), Input Power (W)

$$D=\begin{bmatrix} 2550 & 17 & 50 \\ 3800 & 20 & 60 \\ 5300 & 22 & 100 \\ 6700 & 25 & 100 \\ 7500 & 28 & 120 \\ 3700 & 33 & 60 \\ 4100 & 40 & 50 \end{bmatrix}$$

Step 2. Calculating the normalized specification matrix. This normalization helps to provide the dimensionless elements of the matrix in the 0-1 range. Normalized specification matrix of ultrasonic transducer is calculated as shown below in the equation (4.14)

$$n_{i,j}= \frac{d_{ij}}{\sqrt{\sum_{i=1}^{m} d_{ij}^2}}$$

$$N=\begin{bmatrix} 0.1897 & 0.2342 & 0.2316 \\ 0.2827 & 0.2755 & 0.2779 \\ 0.3943 & 0.3030 & 0.4632 \\ 0.4985 & 0.3443 & 0.4632 \\ 0.5579 & 0.3857 & 0.5558 \\ 0.2753 & 0.4545 & 0.2779 \\ 0.3050 & 0.5509 & 0.2316 \end{bmatrix} \quad (4.14)$$

Step 3. Construction of Relative importance matrix A.

A group of experts will determine will determine the relative importance of the specification with respect to each other.

$$A=\begin{bmatrix} 1 & 5/7 & 5/6 \\ 7/5 & 1 & 7/6 \\ 6/5 & 6/7 & 1 \end{bmatrix}$$

Step 4. Finding out the maximum Eigen value of the relative importance matrix A. Eigen value can be calculated as shown below in the equation (4.15).

$$[A- \lambda I] = 0 \quad (4.15)$$

$$\begin{bmatrix} 1-\lambda & 5/7 & 5/6 \\ 7/5 & 1-\lambda & 7/6 \\ 6/5 & 6/7 & 1-\lambda \end{bmatrix} = 0$$

$$\lambda_{max} = 3$$

Weights are calculated for each parameter using the Eigenvector associated with a maximum Eigen value by using equations (4.16) and (4.17).

$$[A-\lambda_{max} I][w] = 0$$

$$\begin{bmatrix} -2 & 5/7 & 5/6 \\ 7/5 & -2 & 7/6 \\ 6/5 & 6/7 & -2 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} = 0 \quad (4.16)$$

and

$$\sum_{i=1}^{3} w_i = 1 \quad (4.17)$$

We get w_1 = 0.277

w_2= 0.388

w_3= 0.334

Step 5. Calculating the weighted normalized specification matrix. This matrix is calculated by multiplying weights of respective specifications by normalized specification matrix N.

$$V=\begin{bmatrix} 0.0525 & 0.0909 & 0.0774 \\ 0.0783 & 0.1069 & 0.0928 \\ 0.1092 & 0.1176 & 0.1547 \\ 0.1381 & 0.1336 & 0.1547 \\ 0.1545 & 0.1497 & 0.1856 \\ 0.0763 & 0.1763 & 0.0928 \\ 0.0845 & 0.2138 & 0.0774 \end{bmatrix}$$

This weighted normalized specification matrix is all- inclusive matrix, which takes care of the parameter values and their relative importance.

Step 6. TOPSIS method for ranking

The weighted normalized parameters for the best and worst ultrasonic transducer can be obtained as

Next we determine the ideal solution v_i^* and the negative ideal solution v_i^- by choosing from V matrix the maximum and minimum values of the parameter as shown below in the equations (4.18) and (4.19)

$$v_i^* =\{[\overset{max}{_{j=1;i=1,m}}v(i,j)],[\overset{max}{_{j=2;i=1,m}}v(i,j)],\ldots\ldots[\overset{max}{_{j=n;i=1,m}}v(i,j)]\}$$

$$v_i^- = \{[\overset{min}{_{j=1;i=1,m}}v(i,j)],[\overset{min}{_{j=2;i=1,m}}v(i,j)],\ldots..[\overset{min}{_{j=n;i=1,m}}v(i,j)]\}$$

$$v_i^* = (0.1545, 0.2138, 0.1856) \quad (4.18)$$

$$v_i^- = (0.0525, 0.0909, 0.0774) \quad (4.19)$$

Then we calculate separation measures of each alternative i.e. ultrasonic transducer from v_i^* and v_i^-

The separation from ideal solution measured by the n- dimensional Euclidean distance between the i^{th} Ultrasonic transducer and the ideal solution can be calculated as shown below in the equation (4.20).

$S_i^* = [\sum_{j=1}^{n}(v_{ij}-v_i^*)^2]^{1/2}$ (4.20).

The separation from negative ideal solution measured by the n- dimensional Euclidean distance between the i^{th} Ultrasonic transducer and the negative ideal solution can be calculated as shown below in the equation (4.21).

$S_i^- =[\sum_{j=1}^{n}(v_{ij}- v_i^-)^2]^{1/2}$ (4.21).

S_1^*= 0.1929 S_1^- = 0

S_2^*= 0.1608 S_2^- = 0.0340

S_3^*= 0.1107 S_3^-= 0.0995

S_4^*= 0.0875 S_4^-= 0.1230

S_5^* = 0.0641 S_5^-= 0.1599

S_6^*= 0.1270 S_6^-= 0.0899

S_7^*= 0.1289 S_7^-= 0.1270

Step 7:- Relative closeness to the ideal solution of i^{th} Ultrrasonic transducer can be calculated as shown below in the equation (4.22).

$C_i^* = \frac{S_n}{(S_b+S_n)}$ (4.22)

C_1^*=0

C_2^*= 0.1745

C_3^*= 0.4734

C_4^*= 0.5843

C_5^*= 0.7138

C_6^*= 0.4145

C_7^*= 0.4963

Table 4.11 Ranking of Ultrasonic Transducer in Ascending order on the basis of TOPSIS method

Sr.No.	**Relative Closeness to Ideal Solution**	**Value**
1	C_5^*	0.7138
2	C_4^*	0.5843

3	C_7^*	0.4963
4	C_3^*	0.4734
5	C_6^*	0.4145
6	C_2^*	0.1745
7	C_1^*	0

In TOPSIS method as the value of C_5 is highest so ultrasonic transducer BJC-28120D-50HMPZT8 is best and as the value of C_1 is lowest so ultrasonic transducer BJC-1750D-35HNPZT8 is worst .

4.2.2Line Graph Method

$$V = \begin{bmatrix} 5.25 & 3.03 & 3.87 \\ 7.83 & 3.56 & 4.64 \\ 10.92 & 3.92 & 7.74 \\ 13.81 & 4.45 & 7.74 \\ 15.45 & 4.99 & 9.28 \\ 7.63 & 5.88 & 4.64 \\ 8.45 & 7.13 & 3.87 \end{bmatrix}$$

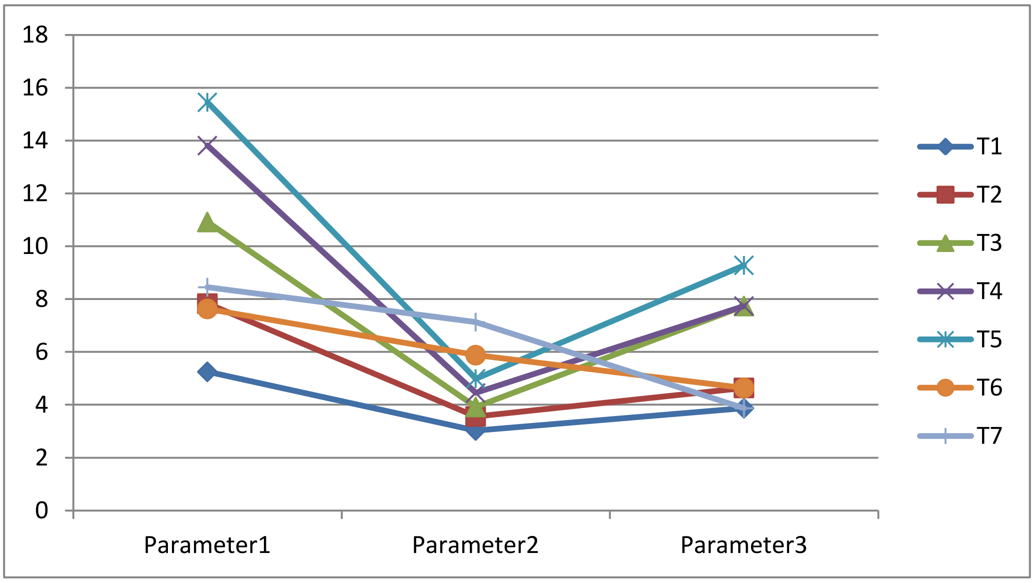


Fig.4.9 Line graph plot for the specifications of Ultrasonic Transducer and the area under curve is shaded

In Fig. 4.9 T1,T2,T3,T4,T5,T6,T7 represents type of ultrasonic transducer i.e. BJC-1750D-35HNPZT8, BJC-2060D-38HNPZT8, BJC-22100D-45HNPZT8, BJC-25100D-68HMPZT4, BJC-28120D-50HMPZT8, BJC-3360D-38HNPZT8, BJC-4050D-35HMPZT4 respectively whereas Parmeter1, Parameter2, Parameter3 corresponds to Static Capacity , Frequency and Input Power respectively.

Step 1 :- - Area under the line graph of order of i^{th} Ultrasonic Transducer can be calculated as shown below in the equation (4.23)

AV_i^L = [$v_{i,1}$+ 2($v_{i,2}$+……………+ $v_{i,n-1}$) + $v_{1,n}$] /2 (4.23)

AV_1^L = [5.25 + 2(3.03) + 3.87]/2 = 7.59

AV_2^L = [7.83 +2(3.56) + 4.64]/2 =9.795

AV_3^L = [10.92 +2 (3.92) + 7.74]/2 = 13.25

AV_4^L = [13.81 +2(4.45) + 7.74]/2 = 15.225

AV_5^L=[15.45 + 2(4.99) + 9.28]/2 = 17.355

AV_6^L= [7.63 + 2(5.88) + 4.64]/2 = 12.015

AV_7^L = [8.45 +2(7.13) + 3.87]/2 =13.29

Step2 :- Identification of Benchmark Ultrasonic Transducer

The highest area out of seven area calculated above is taken as benchmark Ultrasonic Transducer i.e. AV_5^L

AV_B^L = AV_5^L $=$17.355

Step3:- Coefficient of Similarity (COS) based on the weighted normalized specification matrix of i^{th} Ultrasonic Transducer in Line Graph method is given in the equation (4.24) :-

COS_i^{VL}= AV_i^L / AV_B^L (4.24)

Where AV_i^L Area of i^{th} Ultrasonic Transducer in Weighted Normalized matix in Line Graph method

And AV_B^LArea of benchmark Ultrasonic Transducer in Weighted Normalized matrix in Line Graph method

COS_1^{VL} = 7.59/17.355= 0.4373

COS_2^{VL}= 9.795/17.355=0.5644

COS_3^{VL} = 13.25/17.355= 0.7635

COS_4^{VL} = 15.225/17.355=0.8773

COS_5^{VL}= 17.355/17.355=1

COS_6^{VL}= 12.015/17.355=0.6923

COS_7^{VL}= 13.29/17.355=0.7658

Table 4.12 Ranking of Ultrasonic transducer in Ascending order on the basis of Line Graph

Sr.No.	COS_i^{VL}	Value
1	COS_5^{VL}	1
2	COS_4^{VL}	0.8773
3	COS_7^{VL}	0.7658
4	COS_3^{VL}	0.7635
5	COS_6^{VL}	0.6923
6	COS_2^{VL}	0.5644
7	COS_1^{VL}	0.4373

In line graph as the value of COS_5^{VL} is highest so ultrasonic transducer BJC-28120D-50HMPZT8 is best and as the value COS_1^{VL} is lowest so ultrasonic transducer BJC-1750D-35HNPZT8 is worst .

4.2.3Spider Diagram Method

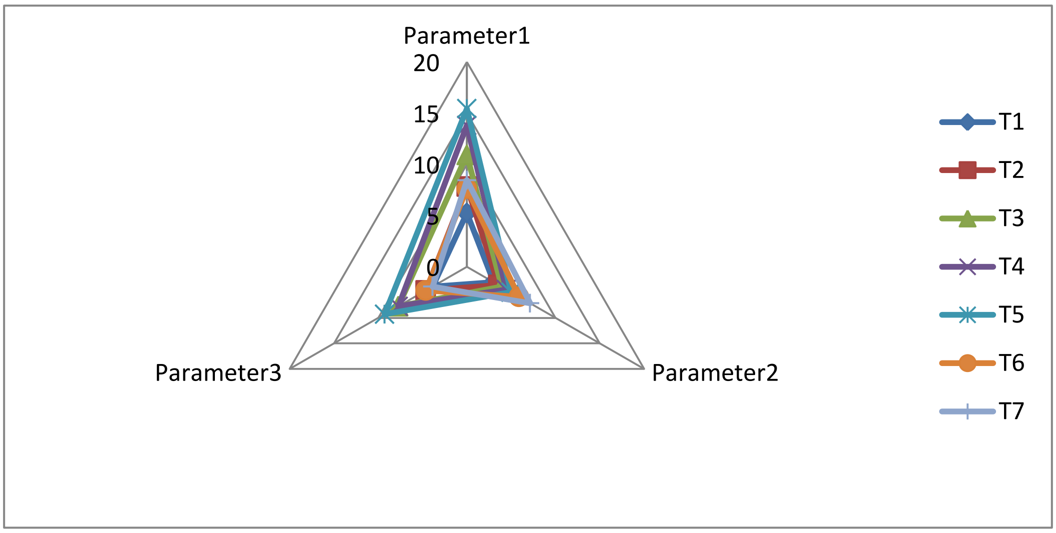


Fig. 4.10 Spider diagram polygon plot for the specifications of ultrasonic transducer and the area enclosed is shaded

In Fig. 4.10 T1,T2,T3,T4,T5,T6,T7 represents type of ultrasonic transducer i.e. BJC-1750D-35HNPZT8, BJC-2060D-38HNPZT8, BJC-22100D-45HNPZT8, BJC-25100D-68HMPZT4, BJC-28120D-50HMPZT8, BJC-3360D-38HNPZT8, BJC-4050D-35HMPZT4 respectively whereas Parmeter1, Parameter2, Parameter3 corresponds to Static Capacity , Frequency and Input Power respectively.

Step 1:- Area under the Spider diagram of order of i^{th} Ultrasonic Transducer can be calculated as shown below in the equation (4.25)

$$AV_i^S = \frac{\sin\theta}{2}\left[\sum_{j=1}^{n} v_{ij}v_{i,j+1}\right] \text{ where } v_{i,n+1} = v_{i,1} \qquad (4.25)$$

And θ = 2π/n where θ= angle between parameter axis n = number of parameters

θ = 2π/3 = 120°

$AV_1^S = \frac{\sin 120}{2}$ [(5.25*3.03) + (3.03 * 3.87) +(3.87*5.25)] =20.7634

$AV_2^S = \frac{\sin 120}{2}$ [(7.83*3.56) + (3.56* 4.64) +(4.64 *7.83)]=34.955

$AV_3^S = \frac{\sin 120}{2}$ [(10.92 *3.92) + (3.92*7.74) + (7.74 *10.92)]= 68.27

$AV_4^S = \frac{\sin 120}{2}$[(13.81*4.45) +(4.45 * 7.74) + (7.74 *13.81)]= 87.81

$AV_5^S = \frac{\sin 120}{2}$ [(15.45*4.99) + (4.99* 9.28) + (9.28 *15.45)]= 115.52

$AV_6^S = \frac{\sin 120}{2}$ [(7.63*5.88) +(5.88*4.64) + (4.64*7.63)]= 46.57

$AV_7^S = \frac{\sin 120}{2}$[(8.45 * 7.13) +(7.13 * 3.87) +(3.87 *8.45)]= 52.20

Step 2 :- Identification of Benchmark Ultrasonic transducer

The highest area out of seven areas calculated above is taken as benchmark Ultrasonic transducer i.e. AV_5^S

$AV_B^S = AV_5^S = 115.52$

Step3:- Coefficient of Similarity (COS) based on the weighted normalized specification matrix of i^{th} Ultrasonic Transducer in Spider diagram method is given in the equation (4.26) :-

$$COS_i^{VS} = AV_i^S / AV_B^S \qquad (4.26)$$

Where AV_i^S Area of i^{th} Ultrasonic Transducer in Weighted Normalized matix in Spider diagram method

And AV_B^S Area of benchmark Ultrasonic Transducer in Weighted Normalized matrix in Spider Diagram method

COS_1^{VS}= 20.7634/115.52 = 0.1797

COS_2^{VS} = 34.955/115.52 = 0.3026

COS_3^{VS}= 68.27/115.52 =0.5909

COS_4^{VS}= 87.81/115.52 =0.7601

COS_5^{VS} =115.52/115.52 =1

COS_6^{VS}= 46.57/115.52=0.4031

COS_7^{VS} = 52.20/115.52 =0.4519

Table 4.13 Ranking of Ultrasonic Transducer in Ascending order on the basis of Spider Diagram

Sr.No.	COS_i^{VS}	Value
1	COS_5^{VS}	1
2	COS_4^{VS}	0.7601
3	COS_3^{VS}	0.5909
4	COS_7^{VS}	0.4519
5	COS_6^{VS}	0.4031
6	COS_2^{VS}	0.3026
7	COS_1^{VS}	0.1797

In spider diagram as the value of COS_5^{VS} is highest so ultrasonic transducer BJC-28120D-50HMPZT8is best and as the value of COS_1^{VS} is lowest so ultrasonic transducer BJC-1750D-35HNPZT8 is worst .

Table 4.14 Evaluation and Ranking of ultrasonic transducer using various methods

Ultrasonic transducer	TOPSIS-closeness to +ve benchmark ultrasonic transd ucer	Rank based on C^*	COS based on Line Graph COS^{VL}	Rank based on COS^{VL}	COS based on Spider Diagram COS^{VS}	Rank based on COS^{VS}
BJC-1750D-35HNPZT8	0	7	0.4374	7	0.1797	7
BJC-2060D-38HNPZT8	0.1745	6	0.5644	6	0.3026	6
BJC-22100D-45HNPZT8	0.4734	4	0.7635	4	0.5909	3
BJC-25100D-68HMPZT4	0.5843	2	0.8773	2	0.7601	2
BJC-28120D-50HMPZT8	0.7138	1	1	1	1	1
BJC-3360D-38HNPZT8	0.4145	5	0.6923	5	0.4031	5
BJC-4050D-35HMPZT4	0.4963	3	0.7658	3	0.4519	4

Table 4.15 Ranking of ultrasonic transducer based on Comparison of three methods

Ultrasonic Transducer	Ranking
BJC-28120D-50HMPZT8	1
BJC-25100D-68HMPZT4	2
BJC-4050D-35HMPZT4	3
BJC-22100D-45HNPZT8	4
BJC-3360D-38HNPZT8	5
BJC-2060D-38HNPZT8	6
BJC-1750D-35HNPZT8	7

Role of User in selection

Ranking done by TOPSIS method and Line Graph method comes out to be same but differs from Spider Diagram method. Before final decision taken to buy the Ultrasonic Transducer the following points come into picture (1) Economic Consideration (2) Availability (3) International market policies , which were not previously considered in coding and evaluation. However even if the above consideration , say economic consideration doesn't allow the user to buy top ranked ultrasonic transducer , the user knows which one to go for the next choice . In this Example as the cost of 1^{st} and 2^{nd} ranked ultrasonic transducer i.e. BJC-28120D-50HMPZT8 and BJC-25100D-68HMPZT4 is higher than the 3^{rd} ranked ultrasonic transducer i.e. BJC-4050D-35HMPZT4 , so BJC-4050D-35HMPZT4 is considered to be the best ultrasonic transducer.

Example 4.3:-

Table 4.16 Specification of ultrasonic drilling machines

Sr. no.	Models	Voltage	Frequency	Power	(Max.Drilling Capacity)
1	Ultrasonic manual drilling machine [51]	220	20	650	6
2	Ultrasonic drilling machine [52]	110	19.5	200	6
3	USD 25[53]	220	25	100	6
4	USD 100 [53]	220	25	250	10
5	USD 150 [53]	220	25	250	25

4.3.1 TOPSIS method

Step 1:- Formation of Decision matrix , 'D' , i.e. matrix will contain all magnitudes of specifications of ultrasonic drilling machines . The rows of matrix are models of ultrasonic drilling machine used and column represent its specification i.e. Voltage , Frequency, Power and drilling capacity

$$D=\begin{bmatrix} 220 & 20 & 650 & 6 \\ 110 & 19.5 & 200 & 6 \\ 220 & 25 & 100 & 6 \\ 220 & 25 & 250 & 10 \\ 220 & 25 & 250 & 25 \end{bmatrix}$$

Step 2. Calculating the normalized specification matrix. This normalization helps to provide the dimensionless elements of the matrix in the 0-1 range. Normalized specification matrix can be calculated as shown below in the (4.27)

$$n_{i,j} = \frac{d_{ij}}{\sqrt{\sum_{i=1}^{m} d_{ij}^2}} \tag{4.27}$$

$$N = \begin{bmatrix} 0.4851 & 0.3881 & 0.8409 & 0.2079 \\ 0.2425 & 0.3784 & 0.2587 & 0.2079 \\ 0.4851 & 0.4852 & 0.1294 & 0.2079 \\ 0.4851 & 0.4852 & 0.3234 & 0.3465 \\ 0.4851 & 0.4852 & 0.3234 & 0.8662 \end{bmatrix}$$

Step 3. Construction of Relative importance matrix A.

A group of experts will determine will determine the relative importance of the specification with respect to each other.

$$A=\begin{bmatrix} 1 & 4/8 & 4/9 & 4/5 \\ 8/4 & 1 & 8/9 & 8/5 \\ 9/4 & 9/8 & 1 & 9/5 \\ 5/4 & 5/8 & 5/9 & 1 \end{bmatrix}$$

Step 4. Finding out the maximum Eigen value of the relative importance matrix A. Eigen value can be calculated as shown below in the equation (4.28).

$$[A- \lambda I] = 0 \tag{4.28}$$

$$\begin{bmatrix} 1-\lambda & 4/8 & 4/9 & 4/5 \\ 8/4 & 1-\lambda & 8/9 & 8/5 \\ 9/4 & 9/8 & 1-\lambda & 9/5 \\ 5/4 & 5/8 & 5/9 & 1-\lambda \end{bmatrix} = 0$$

$\lambda_{max} = 4$

Weights are calculated for each parameter using the Eigenvector associated with a maximum Eigen value by using equations (4.29) and (4.30)

$$[A- \lambda_{max} I][w] = 0$$

$$\begin{bmatrix} -3 & 1/2 & 4/9 & 4/5 \\ 2 & -3 & 8/9 & 8/5 \\ 9/4 & 9/8 & -3 & 9/5 \\ 5/4 & 5/8 & 5/9 & -3 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = 0 \qquad (4.29)$$

And $\sum_{i=1}^{4} w_i = 1$ (4.30)

On calculating , we get

$w_1 = 0.15406$

$w_2 = 0.3078$

$w_3 = 0.3461$

$w_4 = 0.1923$

Step 5. Calculating the weighted normalized specification matrix.

$$V = \begin{bmatrix} 0.0747 & 0.1195 & 0.2910 & 0.0399 \\ 0.0374 & 0.1165 & 0.0895 & 0.0399 \\ 0.0747 & 0.1493 & 0.0448 & 0.0399 \\ 0.0747 & 0.1493 & 0.1119 & 0.0666 \\ 0.0747 & 0.1493 & 0.1119 & 0.1666 \end{bmatrix}$$

This weighted normalized specification matrix is all- inclusive matrix, which takes care of the parameter values and their relative importance.

Step 6. TOPSIS method for ranking

The weighted normalized parameters for the best and worst ultrasonic machining system can be obtained as

Next we determine the ideal solution v_i^* and the negative ideal solution v_i^- by choosing from V matrix the maximum and minimum values of the parameter as shown below in the equations (4.31) and (4.32)

$$v_i^* = \{[\,{}_{j=1;i=1,m}^{max} v(i,j)\,], [\,{}_{j=2;i=1,m}^{max} v(i,j)\,], \ldots\ldots [\,{}_{j=n;i=1,m}^{max} v(i,j)\,]\}$$

$$v_i^- = \{[\,{}_{j=1;i=1,m}^{min} v(i,j)\,], [\,{}_{j=2;i=1,m}^{min} v(i,j)\,], \ldots\ldots [\,{}_{j=n;i=1,m}^{min} v(i,j)\,]\}$$

V^* = (0.0747, 0.1493, 0.2910, 0.1666) (4.31)

V^- = (0.0374, 0.1165,0.0448,0.0399) (4.32)

Then we calculate separation measures of each alternate i.e. ultrasonic drilling machine from v_i^* and v_i^-

The separation from ideal solution measured by the n- dimensional Euclidean distance between the i^{th} Ultrasonic drilling machine and the ideal solution can be calculated as shown below in the equation (4.33).

$$S_i^* = [\sum_{j=1}^{n}(v_{ij}-v_i^*)^2]^{1/2} \qquad (4.33)$$

The separation from negative ideal solution measured by the n- dimensional Euclidean distance between the i^{th} Ultrasonic drilling machine and the negative ideal solution can be calculated as shown below in the equation (4.34).

$$S_i^- =[\sum_{j=1}^{n}(v_{ij}- v_i^-)^2]^{1/2} \qquad (4.34)$$

S_1^* = 0.1302 S_1^- = 0.2490

S_2^* = 0.2432 S_2^- = 0.0447

S_3^* = 0.2769 S_3^- = 0.0497

S_4^* = 0.2051 S_4^- = 0.0876

S_5^* = 0.1791 S_5^- = 0.1517

Step 7:- Relative closeness to the ideal solution of i^{th} ultrasonic drilling machine can be calculated as shown below in the equation (4.35)

$$C^* = \frac{S_i^-}{S_i^+ + S_i^-} \qquad (4.35)$$

C_1^* = 0.6566

C_2^* = 0.1553

C_3^* = 0.1522

C_4^* = 0.2993

C_5^* = 0.4586

Table 4.17 Ranking of ultrasonic drilling machine in Ascending order on the basis of TOPSIS method

Sr. no.	Relative Closeness to ideal Solution	Value
1	C_1^*	0.6566
2	C_5^*	0.4586
3	C_4^*	0.2993
4	C_2^*	0.1553
5	C_3^*	0.1522

On the basis of TOPSIS method as the value of C_1^* is highest so Ultrasonic manual drilling machine is best ultrasonic drilling machine and as the value of C_3^* is lowest so USD 25 is worst ultrasonic drilling machine.

4.3.2 Line Graph Method

$$V = \begin{bmatrix} 2.49 & 5.975 & 5.82 & 3.99 \\ 1.25 & 5.825 & 1.79 & 3.99 \\ 2.49 & 7.465 & 0.896 & 3.99 \\ 2.49 & 7.465 & 2.238 & 6.66 \\ 2.49 & 7.465 & 2.238 & 16.66 \end{bmatrix}$$

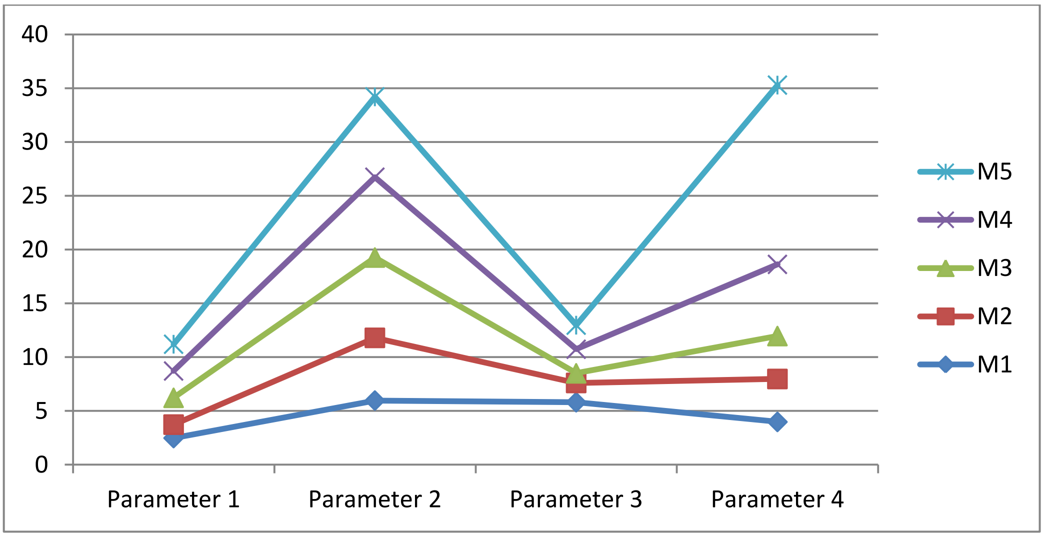


Fig.4.11 Line graph plot for the specifications of Ultrasonic Drilling machines and the area under curve is shaded

In Fig. 4.11 M1,M2,M3,M4,M5 represents ultrasonic manual drilling machine, ultrasonic drilling machine ,USD 25,USD 100, USD 150 respectively whereas Parameter1,Parameter2,Parameter3,Parameter4 corresponds to Voltage , Frequency Power, Max.Drilling Capacity

Step 1 :- - Area under the line graph of order of i^{th} Ultrasonic Drilling machine can be calculated as shown below in the equation (4.36)

$$AV_i^L = [\, v_{i,1} + 2(v_{i,2} + \ldots\ldots\ldots\ldots + v_{i,n-1}) + v_{i,n} \,]/2 \qquad (4.36)$$

AV_1^L = [2.49+ 2(5.975+5.82) + 3.99]/2 =15.035

AV_2^L = [1.25 + 2(5.825+1.79) + 3.99]/2= 10.235

AV_3^L = [2.49 + 2(7.465+ 0.896) + 3.99]/2 = 11.601

AV_4^L = [2.49 + 2(7.465 + 2.238) + 6.66]/2 = 14.278

AV_5^L = [2.49 + 2(7.465 + 2.238) + 16.66]/2 = 19.278

Step2 :- Identification of Benchmark Ultrasonic Drilling Machine

The highest area out of seven area calculated above is taken as benchmark Ultrasonic Drilling Machine i.e. AV_5^L

AV_B^L = AV_5^L = 19.278

Step3:- Coefficient of Similarity (COS) based on the weighted normalized specification matrix in Line Graph method is given in the equation (4.37) :-

$$COS_i^{VL} = AV_i^{VL} / AV_B^{VL} \quad (4.37)$$

Where AV_i^{VL} Area of i^{th} Ultrasonic Drilling machine in Weighted Normalized matix in Line Graph method

And AV_B^{VL} Area of benchmark Ultrasonic Drilling Machine in Weighted Normalized matrix in Line Graph method

COS_1^{VL} = 15.035/ 19.278 = 0.7799

COS_2^{VL} = 10.235/19.278 = 0.5309

COS_3^{VL} = 11.601/19.278 = 0.60177

COS_4^{VL} = 14.278/19.278= 0.7406

COS_5^{VL} = 19.278/19.278 = 1

Table 4.18 Ranking of ultrasonic drilling machine in Ascending order on the basis of Line Graph

Sr.No.	COS_i^{VL}	**Value**
1	COS_5^{VL}	1
2	COS_1^{VL}	0.7799
3	COS_4^{VL}	0.7406
4	COS_3^{Vl}	0.60177
5	COS_2^{VL}	0.5309

In line graph method as the value of COS_5^{VL} is highest so USD 150 is best ultrasonic drilling machine and as the value of COS_2^{VL} is lowest so Ultrasonic drilling machine is worst ultrasonic machine.

4.3.3 Spider Diagram Method

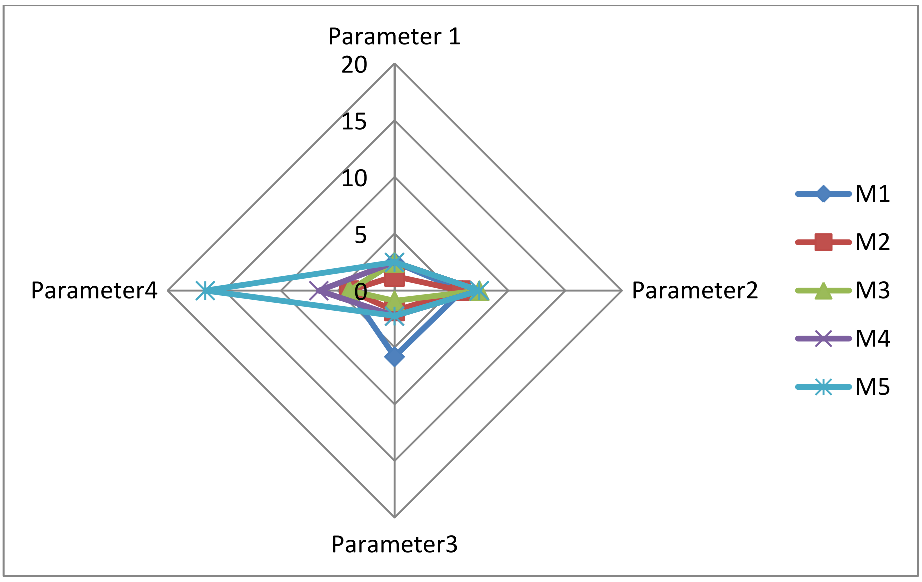


Fig. 4.12 Spider diagram polygon plot for the specifications of ultrasonic drilling machine and the area enclosed is shaded

In Fig. 4.12 M1,M2,M3,M4,M5 represents ultrasonic manual drilling machine, ultrasonic drilling machine ,USD 25,USD 100, USD 150 respectively whereas Parameter1,Parameter2,Parameter3,Parameter4 corresponds to Voltage , Frequency Power, Max.Drilling Capacity

Step 1:- Area under the Spider diagram of order of i^{th} Ultrasonic Drilling Machine can be calculated as shown below in the equation (4.38)

$$AV_i^S = \frac{\sin\theta}{2}\left[\sum_{j=1}^{n} v_{ij} v_{i,j+1}\right] \text{ where } v_{i,n+1} = v_{i,1} \qquad (4.38)$$

And θ = 2π/n where θ = angle between parameter axis n = number of parameters

n=4 ; θ = 2π/4 =90

$AV_1^S = \frac{\sin 90}{2}$ [(2.49*5.975) + (5.975*5.82) +(5.82*3.99) + (3.99*2.49)] = 41.404575

$AV_2^S = \frac{\sin 90}{2}$ [(1.25*5.825) + (5.825*1.79) + (1.79*3.99) + (3.99*1.25)]= 14.9188

$AV_3^S = \frac{\sin 90}{2}$ [(2.49*7.465) + (7.465*0.896)+(0.896*3.99) +(3.99*2.49)]= 19.393315

$AV_4^S = \frac{\sin 90}{2}$ [(2.49*7.465) +(7.465*2.238) + (2.238*6.66) +(6.66*2.49)] =33.3915

$AV_5^S = \frac{\sin 90}{2}$ [(2.49*7.465) + (7.465*2.238) +(2.238*16.66) +(16.66*2.49)] =57.0315

Step2 :- Identification of Benchmark Ultrasonic Drilling Machine

The highest area out of five area calculated above is taken as benchmark Ultrasonic Drilling Machine i.e. AV_5^S

$AV_B^S = AV_5^S$ = 57.0315

Step3:- Coefficient of Similarity (COS) based on the weighted normalized specification matrix of i^{th} Ultrasonic drilling machine in Spider diagram method is given in the equation (4.39) :-

$$COS_i^{VS} = AV_i^{VS} / AV_B^{VS} \quad (4.39)$$

Where AV_i^{VS} Area of i^{th} Ultrasonic Drilling Machine in Weighted Normalized matix in Spider diagram method

And AV_B^{VS} Area of benchmark Ultrasonic Drilling Machine in Weighted Normalized matrix in Spider Diagram method

COS_1^{VS} = 41.404575/57.0315 = 0.72599

COS_2^{VS} = 14.9188/57.0315 = 0.261588

COS_3^{VS} = 19.393315/57.0315 = 0.340045

COS_4^{VS} =33.3915/57.0315 = 0.58549

COS_5^{VS} =57.0315/57.0315 = 1

Table 4.19 Ranking of ultrasonic drilling machines in Ascending order on the basis of Spider Diagram

Sr. No.	COS_i^{VS}	Value
1	COS_5^{VS}	1

2	COS_1^{VS}	0.72599
3	COS_4^{VS}	0.58549
4	COS_3^{VS}	0.340045
5	COS_2^{VS}	0.261588

In Spider diagram as the value of COS_5^{VS} is highest so USD 150 is best ultrasonic drilling machine and COS_2^{VS} is lowest so ultrasonic drilling machine is worst ultrasonic drilling machine

Table 4.20 Evaluation and Ranking of ultrasonic drilling machine using various methods

Ultrasonic Drilling machine	**TOPSIS-closeness to +ve benchmark work piece**	**Rank based on C^***	**COS based on Line Graph COS^{VL}**	**Rank based on COS^{VL}**	**COS based on Spider Diagram COS^{VS}**	**Rank based on COS^{VS}**
Ultrasonic manual drilling machine	0.6566	1	0.7799	2	0.72599	2
Ultrasonic drilling machine	0.1553	4	0.5309	5	0.261588	5
USD 25	0.1522	5	0.60177	4	0.340045	4
USD 100	0.2993	3	0.7406	3	0.58549	3
USD 150	0.4586	2	1	1	1	1

Table 4.21 Ranking of ultrasonic drilling machines based on Comparison of three methods

Ultrasonic Transducer	**Ranking**
USD 150	1
Ultrasonic manual drilling machine	2
USD 100	3
USD 25	4
Ultrasonic drilling machine	5

Role of User in selection

Ranking done by TOPSIS method and two Graphical method vary from each other. Before final decision taken to buy the Ultrasonic Drilling machines the following points come into picture (1) Economic Consideration (2) Availability (3) International market policies , which were not previously considered in coding and evaluation. As the cost of USD 25 is low so user can buy USD 25 .

CHAPTER 5- CONCLUSION AND FUTURE SCOPE

5.1 CONCLUSION

The thesis is focused on modeling, analysis, evaluation and optimum selection of ultrasonic machining system using system approach. Two different methodologies are presented to obtain this motive.

Graph Theoretic Approach is presented in Chapter 3 in order to achieve main motive of developing the model for structural analysis of ultrasonic machining system. This model integrates the different subsystems of ultrasonic machining system and describes the whole system. The contribution of work regarding Graph Theoretic Approach can be summarized as:-

1. This methodology builds a flexible and comprehensive model which has the capability to show the interactions between various subsystems of the complete ultrasonic machining system.
2. The system methodology consists of ultrasonic machining system graph, ultrasonic machining system matrix and ultrasonic machining system permanent function. The system graph is the mathematical representation of subsystem and their interaction, useful for visual modeling and analysis. The ultrasonic machining system matrix is conversion of graph into mathematical form. This matrix is the powerful tool for storage and retrieval of ultrasonic machining system in computer database.
3. The ultrasonic machining system permanent function is a mathematical model characterizing the structure of ultrasonic machining system and also helps one to determine ultrasonic machining system numerical index. This numerical index is used for comparison, ranking and selection of ultrasonic machining system.

Multi-Attribute Decision Making (MADM) Approach is presented in Chapter 4 to achieve the motive of evaluation and optimum selection of ultrasonic machining system from different alternatives available in global market based on the attributes considered. It also provides n-digit coding scheme of ultrasonic machining system depicting the various attributes. It also processes the information about relative importance of attributes for the given application without which inter-attribute comparison is not possible. It presents the result of information processing in terms of suitability index which is used in ranking of ultrasonic machining system according to suitability for the given application.

The contribution of work regarding MADM Approach can be summarized as:-

1. The proposed methodology provides the coding scheme, which is the collection of 50 attributes for characterization of ultrasonic machining system and is useful in defining ultrasonic machining system precisely and accurately. The coding scheme is illustrated with the help of example.
2. A 3-stage selection procedure including elimination search, TOPSIS approach and other graphical methods(Line Graph and Spider Diagram) on the basis of identified pertinent attributes and separation measure of each alternative from generated hypothetically best and worst ultrasonic machining system , helps in ranking of all ultrasonic machining system alternatives available in the global market .
3. The proposed methodology ensures that the selected ultrasonic machining system is nearest to the hypothetically best ultrasonic machining system and farthest from the hypothetically worst ultrasonic machining system.
4. The developed methodology permits the consideration of both types of attributes such as larger the better and smaller the better together and provides the ranking accordingly.
5. Evaluation and ranking of an ultrasonic machining system based on the mathematical and graphical approaches along with illustrated examples are presented.
6. The final choice is made by the user by taking into considerations the various factors i.e. economic considerations, availability etc.
7. It is recommended that the information about all the attributes related to ultrasonic machining system should be maintained as the knowledge base for future usage by the manufacturer. This information will be helpful to himself apart from ultrasonic machining system designer, maintenance personnel, user etc.

5.2 FUTURE SCOPE

1) Graph theory can be applied in other areas of ultrasonic machining system.
2) MADM can be applied to find out the best concentration , power supply required for the machining of brittle and hard material
3) MADM can be applied to find out the best grit size of abrasive, best abrasive which helps in improvement of ultrasonic machining process.
4) Computer software can be developed for solving MADM technique and permanent function.

5) MADM can be applied to various tools used in ultrasonic machining process.

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