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Cutting Dynamics of High Speed Machining of Thin Ribbed Structures

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ABSTRACT:
This investigation is aimed to predict the stable speed range for machining thin-ribbed structures with minimum deflection. Dynamic peripheral milling of a cantilevered free-free-free plate is considered to predict the stable speed range. The significant geometrical parameters considered here are thickness, length and height of the rib. Various thin ribs are modeled by changing the above-mentioned geometrical parameters in order to carry out the analysis. The cutting forces, which were measured experimentally, are applied as input for finite element analysis. Harmonic analysis is carried out for the rib models using which the stable speed range is determined. The influence of cutting forces on the deflection of thin ribs also has been studied. Generalized stable speed is recommended for thin-ribbed structures having different geometrical parameters.

I.INTRODUCTION

High-speed machining is one of the emerging cutting processes having tremendous potential compared to conventional machining processes. High-speed machining centers with 40000rpm-30kW spindles, maximum slide speeds of 1 m/s and maximum accelerations of 10 m/s2, are commonly available. These new technologies make high-speed milling an economically viable alternative to other forms of manufacturing such as forming, casting, and sheet metal build-up. Additionally, high-speed milling processes can produce more accurate and repeatable results, as well as reduce the costs associated with assembly and fixture storage, by allowing several components to be combined into a monolithic machined part. Important applications of high-speed milling include the manufacture of dies and molds, numerous steel and aluminum parts for automobiles, and thin-walled, aluminum components for aircraft [5].High-speed machining not only increases metal removal rates but also results in improved surface finish, burr free edges, dimensional accuracy and a virtually stress free component after machining [6] The aerospace structural components are usually machined from billets and machining involves removal of considerable amount of material. For example, in a case study reported in [7], the airplane part originally weighed 2725 kg and is machined down to 197 kg after many hours on large and heavy machine tools. In such cases, high speeds machining can cut down the machining time appreciably.

Since the machine hour rate of machine tools used in aerospace industry is high, the cost of machining is also high. At very High surface speeds a significant reduction in cutting force is experienced while at the same time causing heat to Transfer mostly to the chip rather than cutter [8]. This fact has generated considerable amount of interest in high speed Machining problems as shown in Fig.1. Machining of thin ribbed structures or thin walled sections is the ongoing development in order to avoid sheet metal buildup or assembly of number of parts.

TABLE I: Comparison of a Conventional Aerospace Fabrication and a Utilized Monolithic Structure

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Variables	Sheet Metal Buildup	Utilized Monolithic Structure
Weight	13.69kg	11.2kg
Parts	39	1
Fasteners	258	0
Assembly	387hrs with 46 tools	242 hrs with zero tools
Flow Time	18 Weeks	14 Weeks

Fig.1. Machining a thin rib with conventional tool and relieved tool.

PROBLEM FORMULATION

A. Problem Identification

Previous literature reveals that dynamic model of peripheral milling of very flexible plate type structures has been considered in determining the milling forces and surface finish form errors, displacements at the tool contact zone [17]. Since only the tool- workpiece contact zone was considered, the dynamic response of the full structure for the given forces may not be realized. Therefore, it is important to consider the model of full structure in carrying out the analysis to predict stable speed range. With this objective, the study is aimed to predict the stable speed range for machining thin ribs with minimum deflection by considering the complete model of thin ribbed structure.

B. Problem Definition

In this work, dynamic peripheral milling of a cantilevered free-free-free plate is considered to predict the stable speed range. The significant geometrical parameters considered here are thickness, length and height of the rib. Various thin ribs are modeled by changing the above-mentioned geometrical parameters in order to arry out the analysis. The cutting forces, which were measured experimentally, are applied as input for finite element analysis. Harmonic analysis is carried out for the rib models using which the stable speed range is determined. The influence of cutting forces on the deflection of thin ribs also has been studied. Generalized stable speed is recommended for thin-ribbed structures having different geometrical parameters. Free vibration analysis of the high speed spindle unit is performed to determine the natural frequency and mode shape which are considered in selecting the stable speed for machining thin ribbed structures in order to avoid resonance problems.

C. Experimental Work

Experiments were carried out on a 3-axis Vertical CNC milling machine fitted with 5 kW high-speed spindle, which has a maximum speed of 40,000 rpm. The workpiece used was aluminum alloy of 6210 grade. A two-flute Titanium Nitride coated solid carbide endmill was used for machining. The diameter of the endmill, helix angle, and radial rake angle are 6 mm, 300 and 20 respectively. A Kistlerpiezo-electric 3– component dynamometer was used for measuring the forces. Teknonix make oscilloscope was used for recording these forces in terms of voltage as shown in Fig.2.

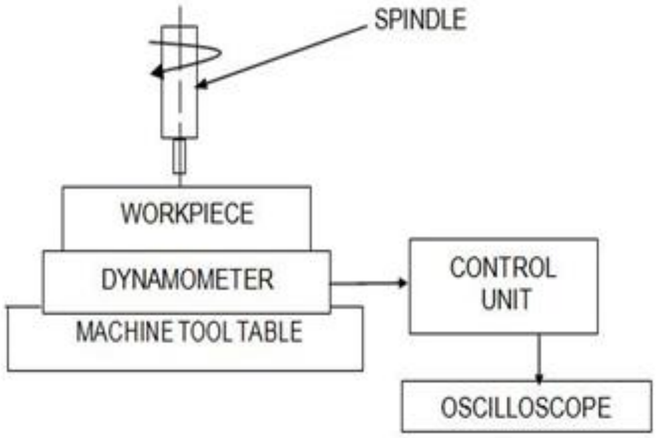

Fig.2. Schematic representation of experimental set

A rectangular block of 90 x 50 x 50 mm shown in Fig. 3 was taken and clamped over the machine tool table. At one end of the block, end-milling process has been done to make thin rib. When the rib thickness was 3mm and the height was 20mm cutting forces were measured in x direction and y direction using dynamometer and oscilloscope. The measured cutting forces in x- direction and the feed forces in y-direction listed in Table 1 are taken as input for the analysis. The forces correspond to a cutting velocity of 453 m/min (spindle speed of 24000 rpm using a 6 mm cutter) and for feed rates varying from 1000 mm/min to 2500 mm/min.

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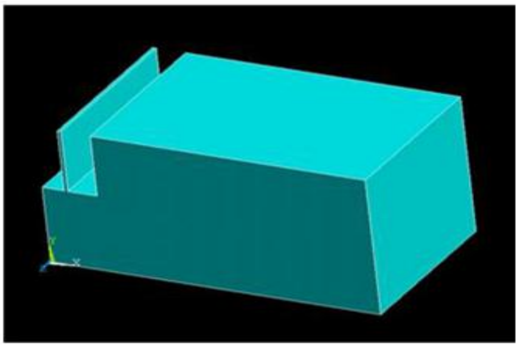

Fig.3.Thinribbed component machined using experimental -setup.

FINITE ELEMENT ANALYSIS

A. Modeling of the Thin Ribbed Structure

The thin-ribbed structure is modeled and analyzed using ANSYS 7.0. Since the structure is a solid model, SOILD92, 3-D 10 node tetrahedral structural solid element has been chosen. SOILD92 element shown in Fig. 4 has quadratic displacement behavior and is well suited to model irregular meshes. The element is defined by 10 nodes having three degrees of freedom at each node, namely, translations in the nodal x, y and z directions. The element has plasticity, stress stiffening, large deflection and large strain capabilities.

Three important parameters to be considered for modeling the thin ribbed structure are thickness, height and length of the rib. Fig. 5 shows the meshed model of the thin ribbed structure which has 30 mm rib height, 50 mm rib length and 2rib thickness. Similarly various thin ribbed structures were modeled by changing the above-mentioned parameters. The geometric parameters that are used for modeling thin ribbed structures are given below.

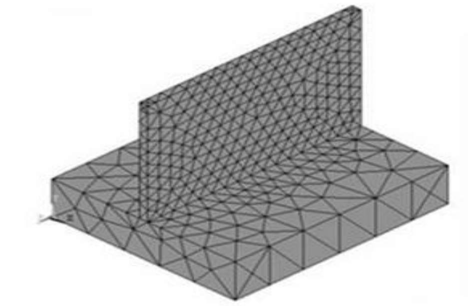

Fig. 4. SOLID92 3-D 10 node tetrahedron element.

- Thickness of the rib (mm): 1, 2, and 3.
- Length of the rib (mm): 50, 100, and 150.
- Height of the rib (mm): 30, 40, 50.

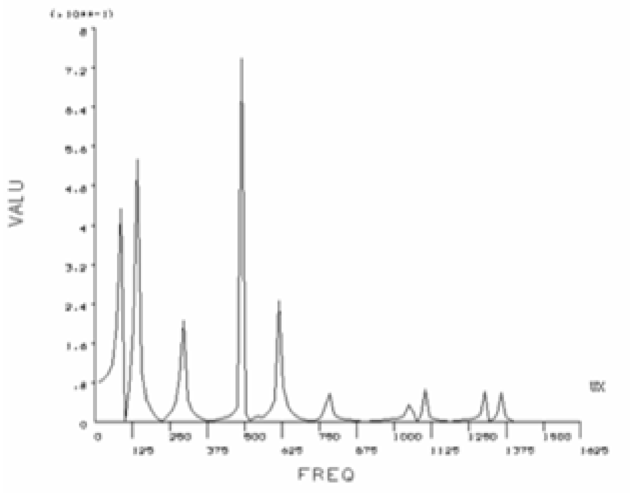

Fig. 5. Meshed model of the thin ribbed structure.

RESULTS AND DISCUSSIONS

The results of harmonic analysis of thin-ribbed structures having different geometric parameters are discussed in the following section.

A. Influence of Rib Thickness on Rib Deflection and Stable Speed

Analysis of Rib of 3 mm Thickness: The rib was modeledwith 3 mm thickness, 30 mm height and 50 mm length and the harmonic analysis was performed. Fig. 6 shows the frequency response of 3 mm thick rib model on applying cutting forces of 30 N in X-direction and 26 N in Z-direction. The stable speed range for machining 3 mm thick rib falls between 875 Hz to 1000 Hz and 1150 Hz -1250 Hz. Fig. 6 shows the deflection in mm in y-axis and the minimum deflection of 4 microns occurs at the frequencies of 900 Hz and 1175 Hz.

Analysis of Rib of 2 mm Thickness: The rib was modeledwith 2 mm thickness, keeping the same rib height and length. Various input forces are applied and the frequency responses for corresponding forces have been attained. Figs. 6 and 7 show the response of the structure corresponding to the forces of 16 N (cutting force) and 21 N respectively.

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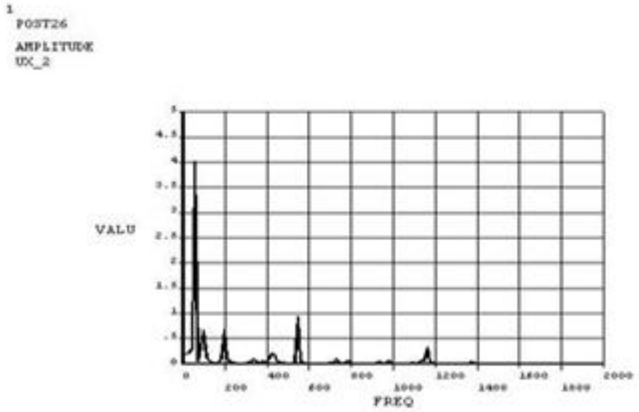

It is found that the rib deflection increases by 25-30% whenthe cutting force is increased by 17-30%. It is also observedfrom Figs. 6 and 7 that the fundamental natural frequency of the ribbed structure decreases from 81 Hz to 55 Hz ondecreasing the rib thickness from 3 mm to 2 mm. It is also found that the minimum deflection falls at the frequency ranges of 800 -900 Hz, 1000 Hz -1100 Hz, and 1200 Hz -1350Hz. Hence, the corresponding stable speed range for achieving required dynamic stiffness of work piece falls between 24000 rpm - 27000 rpm, 30000 rpm - 33000 rpm, and 36000 rpm -40500 rpm. Fig. 8 shows the frequency response of 2mm thick rib structure in log mode from which the deflection pattern for whole range of frequency can be observed and the minimum deflection of 0.01 micron occurs at 850 Hz.

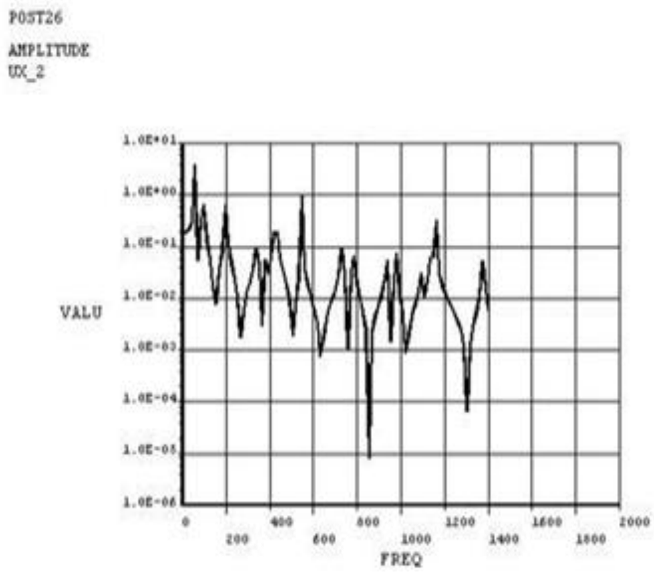

Fig. 8. Frequency response of 2 mm thick rib (log mode).

HIGH SPEED SPINDLE

High speed spindle is an important unit which influence significantly on the dynamics of the machining process. Spindle unit has its own natural frequencies and during machining process, the forcing frequency at which machining is done should not be the natural frequency of the spindle unit in order to avoid the resonance. Hence determining the natural frequency of the spindle unit is very important for selecting the spindle speed for machining. This chapter discuss on the free vibration analysis of the spindle unit. Spindle unit is modeled and the modal analysis is performed to determine the natural frequencies and mode shapes of the spindle.

A. Modeling of the Spindle Unit

High speed spindle used for HSM setup has the following

Specifications:

- Spindle power - 5 kW
- Spindle speed - 40,000 rpm
- The bore diameter - 60 mm.
- Length of the spindle unit - 218 mm

High speed machining is defined by using DN number in which D is the diameter of the spindle bore and N is spindle speed in rpm. For the above mentioned specification the DNnumber is 2.4millions. The spindle unit is modeled usingPro/Engineer imported to Ansys 7 software for performingmodal analysis. The sectional view of the high speed spindleis shown in Fig.9.

Fig. 9. Cut view of high speed spindle model.

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CASE STUDIES - AIRCRAFT STRUCTURES

Three typical aircraft structures having thin ribs areconsidered here for performing harmonic analysis to predict the stable speed ranges. Thin ribbed structures are modeled and modal analysis has been done to find out the natural frequencies followed by harmonic analysis has been performed.

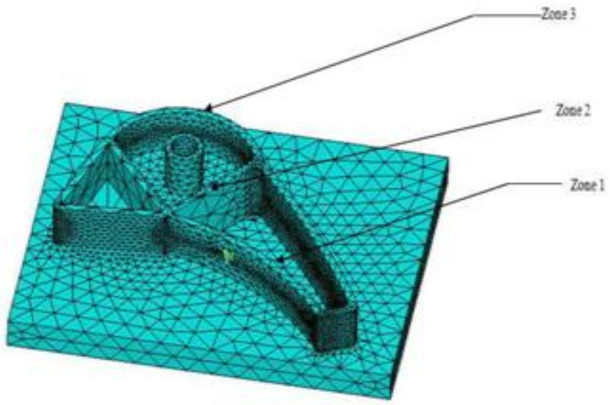

Fig.10. Finite element mesh of the thin-ribbed aircraft structure (Courtesy: Comp machine, USA).

A. Case Study I

A case study of typical aircraft structure shown in Fig10 is considered and finite element harmonic analysis is performed to predict the stable speed range for machining. The structure is modeled in Pro/Engineer and imported to ANSYS. Harmonic analysis is performed by using Solid92, 3-D 10 Node tetrahedral structural solid elements, which has a quadratic displacement behavior and is well suited to model irregular meshes. The element is defined by ten nodes having three degrees of freedom at each node namely translations inThe nodal x, y and z directions. The element has plasticity,Stress stiffening, large deflection and large strain capabilities.As the structure is placed on the machine tool table andclamped at the sides, nodes located at the bottom surface ofthe plate and side walls are constrained in all degrees ofFreedom.

B.Modal Analysis of the Structure

Modal analysis can be used to determine the naturalFrequency and mode shape of the structure. So that thestructure's operating frequency can be identified in order toavoid any harmful effects from natural frequency of theStructure (resonance conditions).

Mode No.	Modal Frequency (Hz)	Mode No.	Modal Frequency (Hz)
1	263	15	799
2	341	16	856
3	390	17	923
4	415	18	961
5	423	19	995
6	458	20	1055
7	499	21	1154
8	578	22	1180
9	594	23	1189
10	667	24	1210
11	671	25	1244
12	707	26	1269
13	709	27	1306
14	717	28	1388

VII. CONCLUSION

The methodology outlined in this work established the theoretical basis for predicting stable speed ranges with minimum rib deflections. The stable speed ranges have been proposed for the influence of cutting forces on deflection of thin ribs has been investigated b. it is recommended that machining of thin ribs with minimum deflection is possible at the frequencies of 1000 Hz (30000 rpm), 1200 Hz (36000 rpm if the geometric parameters of rib changes from 3mm to 1mm by thickness, 50mm – 150mm by length, 30mm – 50mm by height. Free vibration analysis of the high speed spindle units has been done in order to determine the natural frequencies and mode shapes, and it has been considered in determining the stable speed for machining and to overcome resonance problem during matching. In additional four typical case studies have been considered the analysis has been carried out to predict the stable speed range with mini9mum deflection. Initially modal analysis has been performed to determine the natural frequency of the Structure. In each case study, thin ribbed structures have beensegregated into various zones and stable frequency rangeswere found out for each zone by performing harmonicAnalysis. Finally a frequency range for machining thecomplete structure has been recommended. Hence it is possible to realize thin ribs in high speed machining becauseof decrease in cutting forces and increase in the dynamicStiffness of the work piece. This is of significant advantage asFar as aircraft design is concerned.

Scope for Future Work:

From the result of this work, theinvestigation may be continued with the following ways,

- Rib deflection can be measured experimentally usingnecessary equipments and the results from finite elementanalysis can be validated.
- Rib thickness is the most influencing parameter onsurface finish. Hence, influence of rib thickness onsurface finish shall be investigated from which the cuttingconditions may be selected for achieving required surface finish.
- Generalized cutting force model for milling of thin ribbedstructures can be developed so that the predicting cuttingforces will be applied for carrying out the analysis.
- Influence of tool length of rib defection may beinvestigated through finite element analysis so that thelength of the tool can be optimized and used to machiningthin ribs having different heights.

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