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Dynamics of High-speed Machining of Aerospace Structures using Finite-element Analysis

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ABSTRACT

The study is aimed to investigate certain aspects of high-speed machining for improving the accuracy of thin-walled aerospace components. The approach used involved the development of finite-element model of the workpiece to be machined and its subsequent frequency response analysis. The response of the workpiece subjected to dynamic cutting force gives an indication of the best possible speeds from the point of view of accuracy. Based on the results of the analysis, it is possible to predict the range of spindle speeds at which the workpiece demonstrates very high dynamic rigidity. In addition, this study has established the superiority of high-speed machining to produce aerospace structures with high stiffness-to-weight ratio and also throws some light on the capability of high speed in machining of low rigidity sculptured-surface components.

Keywords: High-speed machining, finite-element analysis, thin ribs, harmonic analysis, end-milling, frequency response, aerospace structures, aircraft components, metal removal rate

1. INTRODUCTION

The recent trend in design of aerospace structures is to use large monolithic parts to reduce setup time of individual constituent parts, thereby reducing the cost and the lead time in realising the structure. Such complex parts are designed with ribs to obtain high stiffness-to-weight ratio. The recent trend in machining technology is to use high spindle speeds because of the availability of high performance end-milling tools with exotic coating technologies.

A usual problem in the end-milling of aluminum structures for aerospace applications is that of maintaining good surface finish on either side of thin ribs, which tend to deflect under cutter pressure. If machining is done at conventional speeds, the cutting force tends to deflect thin ribs so that it is not possible to achieve small thickness with dimensional accuracy. The distortion may place a constraint on the achievable thickness of ribs at the desired surface quality. There are a few reports in literature on the successful practical applications of high-speed machining[1].

This study investigates the theoretical analysis of the performance of complex aerospace structure during high-speed machining. The objective of this study is to determine process parameters which will yield improved dimensional accuracy while machining aerospace structures with thin ribs.

1.1 Literature Survey

High-speed machining is one of the emerging cutting processes having tremendous potential for aerospace industry. High-speed machining not only increases metal removal rates but also results in improved surface finish, burr-free edges, dimensional

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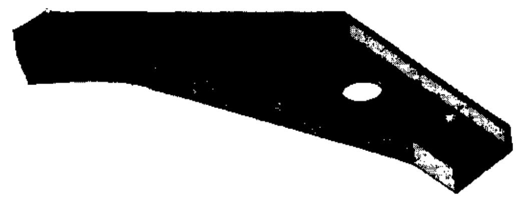
accuracy and a virtually stress-free component after machining[2]. The aerospace structural components are usually machined from billets and machining involves removal of considerable amount of material. For example, in a case study[3], the aeroplane part originally weighed 2725 kg and was machined down to 197 kg on large and heavy machine tools after many hours. In such cases, high-speed 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[4]. This fact has generated considerable amount of interest in high-speed machining.

In aluminum, this effect is pronounced when cutting speed reaches 1300 m/min or higher. This is of substantial benefit when machining thin-walled aluminum aircraft components, one of the major materials used in aerospace industry. In aircraft industry application of high-speed machining makes it more attractive to machine from solid rather than machining components produced from raw material using a near-net shape manufacturing approach. For example, a landing gear could be manufactured economically using high-speed machining[5].

A critical review of literature reveals that most of the studies reported are experimental in nature with little theoretical analysis to establish the superiority of high-speed machining. This has been initiated to understand the process of high-speed machining from an analytical angle. The dynamics of MTWF system and its influence on machining has been of considerable interest to manufacturing engineers for a long time. The technology in recent years has advanced so much that today machine tools, tools and tooling fixtures of very high static and dynamic stiffness are available which have extended the operating range of machine tools significantly. The machining problem in the present study is a peculiar one, where the workpieces have significantly low dynamic stiffness compared to the other subsystems involved in machining. Therefore, focus here is only the workpiece and the contribution of stiffness of other subsystems has been ignored.

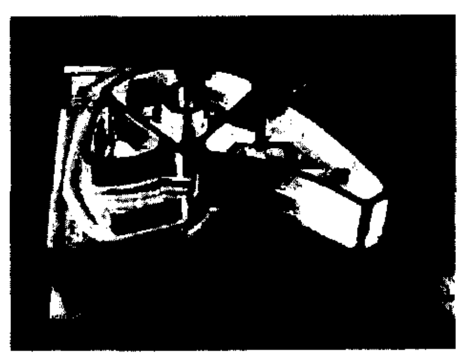
2. PROBLEM DEFINITION

A few typical workpieces representative of aircraft structures are shown in Fig.1. The distinguishing feature of these components is that they are all machined from billets and are ribbed to improve the structural stiffness while keeping the weight of the structure to a minimum. Only simple structures are considered in the analysis to reduce computational time.



(a)

(b)



(c)

Figure 1. *A few typical workpieces representative of aircraft structures:* (a) *aircraft bracket,* (b) *strap-on bracket, and* (c) *aircraft part with ribs.*

The two important geometrical parameters are the thickness and the depth of the rib. The contribution to stiffness (k) by the depth (d) of the rib is significantly more than that of the width (b) ($k \propto wd^3$). Hence, the objective of the designer is to obtain minimum weight with maximum stiffness. Reducing the width introduces the problem of lateral deflection of the rib while pocket-milling. If a is the theoretical interference between the end mill and workpiece during pocketing, and δ is the deflection, the actual depth of cut while machining the rib in its middle is (a–δ). This introduces a dimensional error of δ.

At low speeds of operation, the dynamics of the workpiece is such that the behaviour of the part of the structure closely approximates its static behaviour. The amount of deflection at low frequencies of dynamic cutting force is nearly equal to its static deformation. This puts a serious limitation to the realisation of thin ribs with the required dimensional accuracy. How thin ribs could be machined with the required dimensional accuracy is investigated in this paper.

2.1 Effect of Dynamic Force on Thin Ribs

The cutting force in end-milling is dynamic because of the variation in cutting force. Typical variations of the force when milling a rib are shown in Fig. 2. For a typical 2-lipped end mill, the variation of cutting forces follows this pattern. This dynamic cutting force has a frequency of $2n/60$ Hz, where n is the revolutions per minute(rpm) of the cutter.

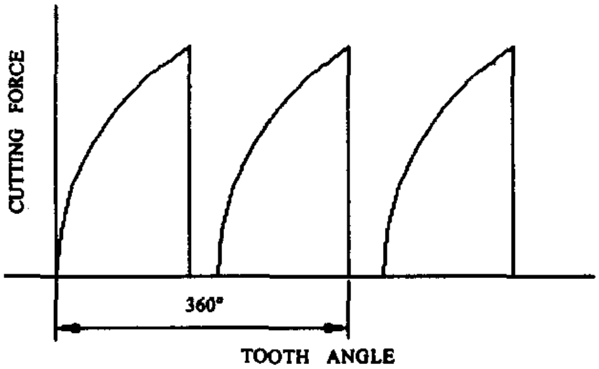


Figure 2. Theoretical cutting force for an interrupted face milling operation (the cutting force changes when the engagement with the workpiece constantly changes during steady operation).

The frequency increases in direct proportion to the number of lips of the end mill and the rpm.

2.1.1 *Finite-element Model*

The structure shown in Fig. 1(a) is modelled in Pro/Engineer and imported to ANSYS. Harmonic analysis is performed using solid92, a 3-D 10-node tetrahedral structural solid element which has a quadratic displacement behaviour 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. Figure 3 shows the finite-element model of the part which has 2380 elements with 5117 nodes and the maximum degrees-of-freedom per

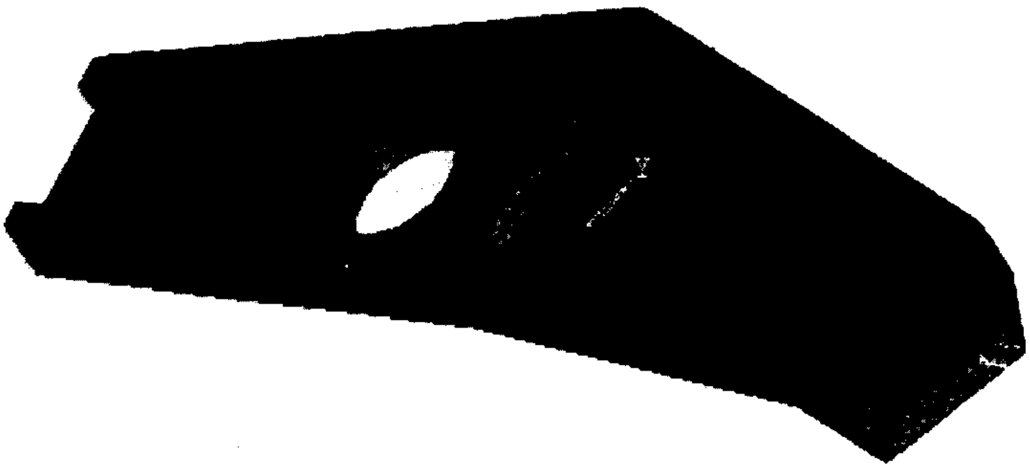


Figure 3. Finite-element model of bracket

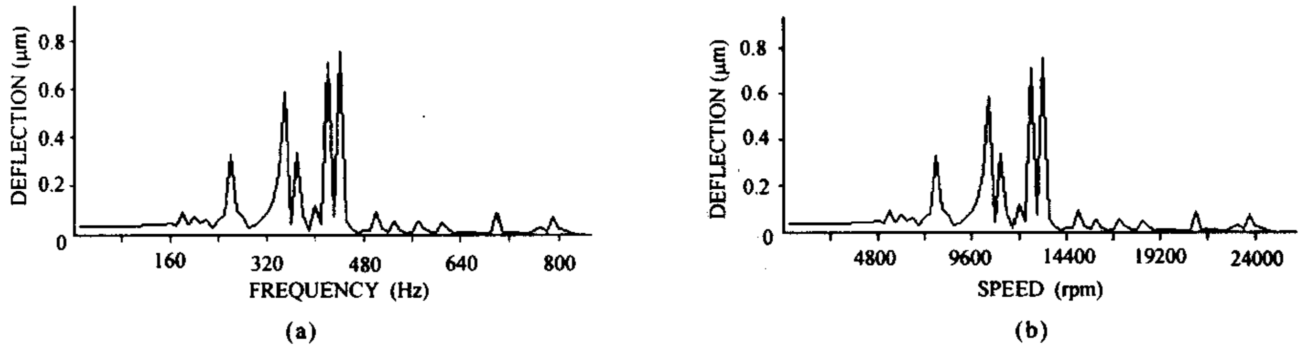


Figure 4. Frequency response of aircraft structure

node is 3. Since the range of high-speed machining is reported between 15,000 rpm and 50,000 rpm, the harmonic frequency range for a 2-lipped cutter will be between 500 Hz and 1600 Hz. This frequency range has been used in this analysis. At low speeds (which represent the conventional end-milling operating speeds), the dynamic stiffness is comparatively very low, resulting in large deflection in the workpiece at the point where machining is done.

To present a general approach to this study, a dynamic simulation of the workpieces shown in Fig. 1 was carried out. The response of these structures for a wide range of spindle speeds is shown in Fig. 4. At higher spindle speeds, all the workpieces exhibit high stiffness.

The model shown in Fig. 3 was subjected to a high frequency dynamic loading. As the workpiece is fixed at both the ends during machining, nodes located at the end faces are constrained in all degrees-of-freedom. A harmonically varying load simulating the effect of cutting force for an interrupted face milling operation of magnitude 500 N is applied at the mid-portion of the rib of the component. A harmonic analysis is performed using full solution method where the full system matrices are used to determine the harmonic response with no matrix reduction.

It is interesting to note that the workpiece demonstrates high dynamic stiffness at higher rpm. A quantitative representation of the resulting rib deflection is shown in Fig. 5. It is noted that the maximum deflection at the tool point when the component is machined at 6000 rpm is 284 µm as shown in Fig. 5(a). At 21,600 rpm, the deflection reduces to 31 µm as shown in Fig. 5(b).

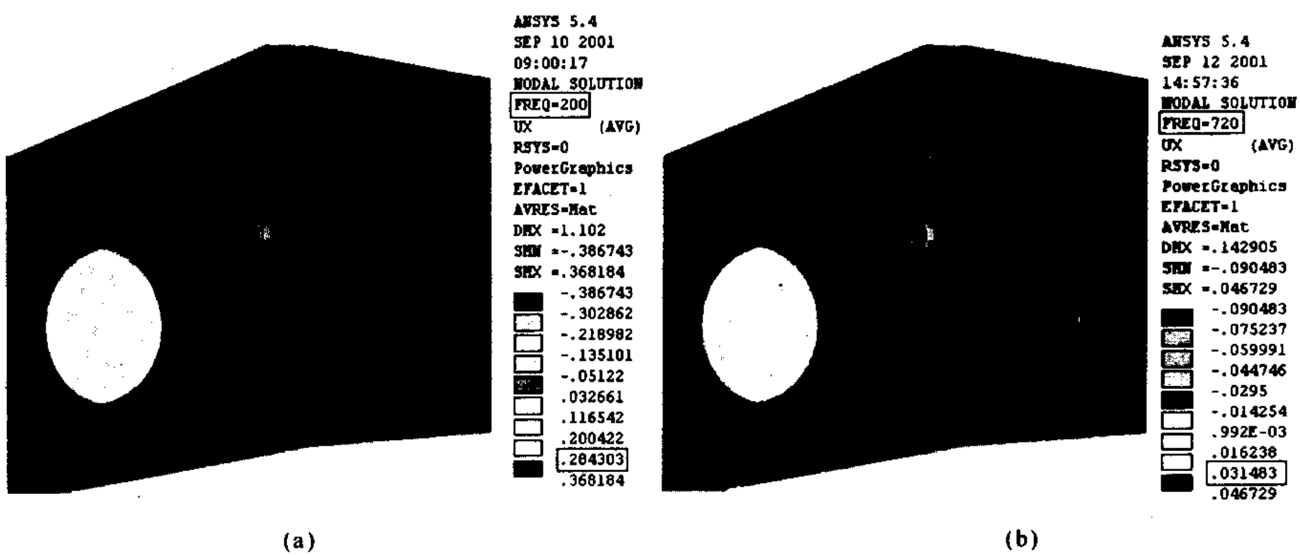


Figure 5. Shows the deflection of rib while pocket-milling at (a) low speed (6,000 rpm) and (b) high speed (21,600 rpm). The harmonic analysis is carried out using ANSYS.

A comparison of Fig. 5(a) with Fig. 5(b) shows that there is significant reduction in the lateral deflection of the rib. An interesting and practically useful conclusion is that with high speeds of operation, thin ribs could be machined with higher accuracy.

CONCLUSIONS

A typical aircraft structural part has numerous pockets. The ribs between the pockets serve as stiffeners. High-speed machining has the twin advantage of high metal removal rate and that it permits part to be designed with low weight-to-stiffness ratio. The very low lateral forces in high-speed machining reduces the deflection of the ribs while machining, and thereby, manufacturing thin-walled designs possible. This is of significant advantage as far as aircraft design is concerned.

Using advanced 5-axis machines, there is no need for expensive, time-intensive multiple-part manufacturing, including laborious setup on different machines and riveting of workpieces together into a finished part. The methodology outlined in this paper establishes the theoretical basis for achieving improvements in part accuracy, quality, and superiority of high-speed machining in realising thin ribs.

The following conclusions are drawn:

- It is possible to realise thin ribs in high-speed machining because of the increase in the dynamic stiffness of the workpiece.
- Increase in spindle speeds means smaller cutters for the same spindle speed. The cutting dimensions are correspondingly reduced, and hence, cutting force. For the same metal removal rate, smaller force results in many advantages, such as
  - Smaller workpiece deflection, and hence, higher accuracy
  - Less energy is used in cutting resulting in less temperature rise in the workpiece. This helps to improve the accuracy. The metallurgical properties of the machined surface are also not affected
  - There will be less residual stresses
- Machining at higher range of stiffness improves the finish of the surface produced.

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