

High Performance Spindle Systems for Heavy Duty Milling of Difficult-To-Cut Aerospace Materials

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ABSTRACT

In order to machine a wide variety of materials with a single spindle and setup, a multi-purpose spindle for machine tools has been developed. The spindle achieves both high power/ torque for heavy duty milling operations and higher rotational speed. The developed spindle is equipped with an additional motor at the back of a conventional induction motor driven spindle to assist the induction motor when high milling torque is needed. For high speed operation, the additional motor can be mechanically disengaged and the spindle can be used as a conventional spindle. A Permanent Magnet Synchronous Motor (PMSM) is adopted for the additional motor, because a highly stable milling operation can be realized by utilizing the advantage of the PMSM. As expected, cutting experiments have shown that the material removal rate has been greatly improved with the developed spindle. Also it was found that machining with the spindle resulted in longer tool life in comparison to machining by the conventional spindle, which is possible through the stability improvement provided by the PMSM torque assistance. A simulation study was also conducted in order to investigate the characteristics of the PMSM and the induction motor used in the dual driven spindle. The results indicated that the PMSM provides a highly stable milling process and a very high performance spindle can be achieved only with a PMSM. Therefore, a high performance built-in PMSM spindle has been developed and introduced in this paper. The PMSM spindle achieves a high bandwidth, and the rotational dynamics of the spindle can also be easily adjusted by introducing a variable dynamic software control for optimizing the cutting process. The experiments suggested that there are optimum setup parameters for the spindle driver in order to maximize the tool life.

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INTRODUCTION

The demands for high efficiency products manufactured by machine tools are increasing in industry. Components of the products tend to become lighter and stronger but also become more complex and very difficult to machine/manufacture due to the inherent properties of the raw materials. In an effort for higher productivity and accuracy of machined parts, multi-tasking machine tools such as 5-axis machining centers and mill-turn machines have widely been used in industry. One of the advantages of such machines is to achieve fully automated machining operations with a single workpiece/machine setup resulting in a remarkable reduction in human intervention time as well as possible error introductions. In such a multi-tasking machine, a versatile spindle satisfying high maximum torque, power and rotational speed is required because productive roughing and

high speed finishing operations must be performed by the same spindle. Recently, opportunities to machine difficult-to-cut materials such as titanium alloys and nickel-based superalloys have rapidly been increasing. To machine a monolithic complex shape made by these materials, such as impellers and blisks used for aerospace engines and gas turbines, very high spindle torque and 5-axis motion are necessary. Although several types of machine tool spindles are currently available, such as built-in motor spindles and gear driven spindles, almost no spindles can be found to have multi-machining functionality to achieve the best productivity and quality.

An induction motor spindle is typically used in a built-in motor spindle, but it is difficult to achieve both high torque and compact size at the same time. In this study, a compact hybrid spindle for modern CNC machine tools has been

proposed and prototyped using an innovative Dual-driven Spindle System (DSS) concept in order to meet the current industrial needs. The spindle performance and characteristics have been investigated through experimentation. Also, theoretical models of the spindle will be introduced in this paper and the spindle characteristics and dynamics have been studied by simulation to analytically evaluate the spindle.

Based on the experimental and simulation results, a built-in PMSM spindle has also been developed aiming at a high bandwidth spindle. The concept of flexible rotational rigidity control using a high performance PMSM has also been covered in this paper. With the PMSM spindle, the spindle rotational characteristics can be adjusted for optimizing the cutting process in order to prevent tools from unwanted premature damage. Simulation models of the spindle motor drive system are presented. The system prototype and feasibility studies are also presented in this paper.

DEVELOPMENT OF DUAL-DRIVEN SPINDLE SYSTEM (DSS)

DSS Design Concept

In order to meet the industrial demands described in the previous section, a Dual-driven Spindle System (DSS) concept has been proposed to achieve high torque without sacrificing rotational speed. Figure 1 illustrates the concept of the spindle. As shown in the figure, an additional motor is coaxially placed at the rear end of a conventional built-in motor spindle system to assist torque for heavy duty machining operations. Although a typical motor for a machine tool spindle is an induction motor, a Permanent Magnet Synchronous Motor (PMSM) is used as the secondary motor because it is commonly known as having following advantages over a conventionally used induction motor [1]:

- Higher power density
- Better power-to-weight ratio
- Better dynamic performance

A mechanical coupling driven by a hydraulic system has been designed as an interface of the spindle main shaft and the PMSM because the PMSM is not designed for high speed operations. When the PMSM with torque T_2 is engaged to the main spindle with an original built-in spindle motor with torque T_1 , the total output torque T becomes, $T=T_1+T_2$, thus, achieving high torque. The advantages of the proposed design concept are high energy efficiency with mechanical simplicity for highly reliable operation without affecting the static and dynamic spindle characteristics. In addition, the direct drive configuration contributes to a dramatic decrease in the spindle rotation fluctuation, and higher inertia of rotational parts also contributes to a stable rotation.

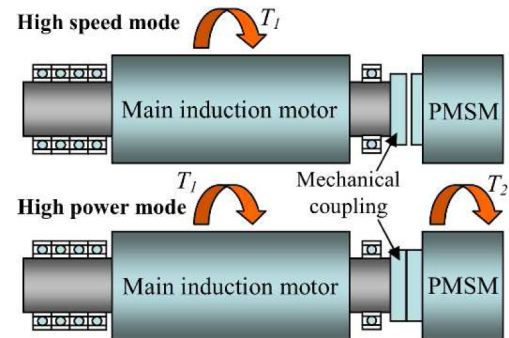


Figure 1. Dual driven spindle concept.

Although the idea of the DSS is simple, there are usually a number of auxiliary mechanisms such as a tool clamp/unclamp system at the end of the spindle system. It is important to design the spindle to be as small as possible especially for multi-tasking machine tools, but the spindle design becomes quite long if the main spindle shaft, PMSM, and the auxiliary mechanisms are simply placed in series. To realize the DSS with the smallest spindle space, the PMSM has been accommodated in the outer space of the auxiliary mechanisms. The idea of the PMSM integration requires a hollow structure. Figure 2 shows the designed PMSM for the DSS. As shown in the figure, the hollow rotor has a space inside where the auxiliary mechanisms can be integrated to achieve the smallest design. The hollow large diameter PMSM design is also advantageous to achieve high torque. When designing the PMSM, careful design consideration must be taken for optimizing for the PMSM by fully utilizing electromagnetic field FEM analysis.

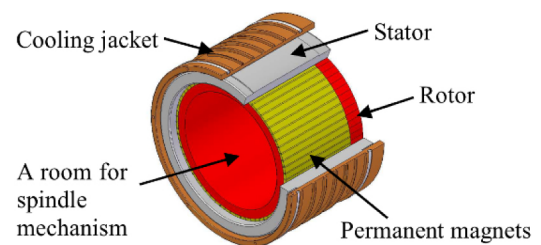


Figure 2. Hollow PMSM structure for the DSS.

Design of DSS Prototype

The DSS prototype was designed by modifying an existing built-in motor type spindle. The performance of the existing spindle is shown in Figure 3. The prototype of the DSS has been designed by developing the PMSM to be integrated in the original built-in induction motor type spindle. The maximum torque and power will be enhanced to 1819Nm and 75.5kW at the maximum duty rating as shown in Figure 4. It is estimated that 2 times higher Material Removal Rate (MRR) can be achieved with the DSS prototype by considering the power rating of the two motors as compared to the original spindle. The maximum torque of

the DSS is approximately 1.8 times higher than that of the original spindle and it is especially advantageous for heavy duty machining of various materials including difficult-to-machine aerospace materials.

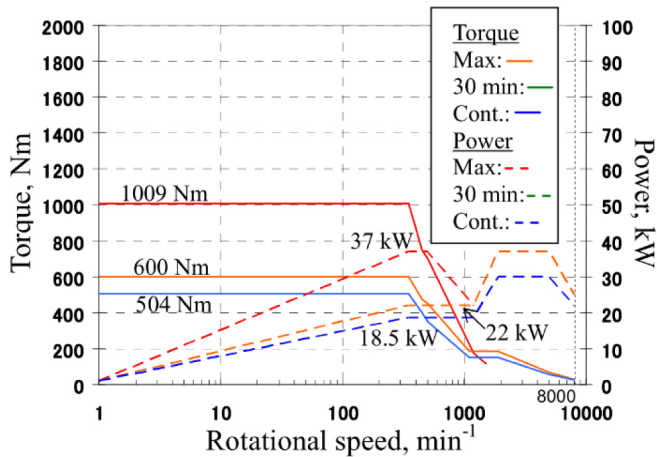


Figure 3. Characteristics curve of original built-in motor spindle.

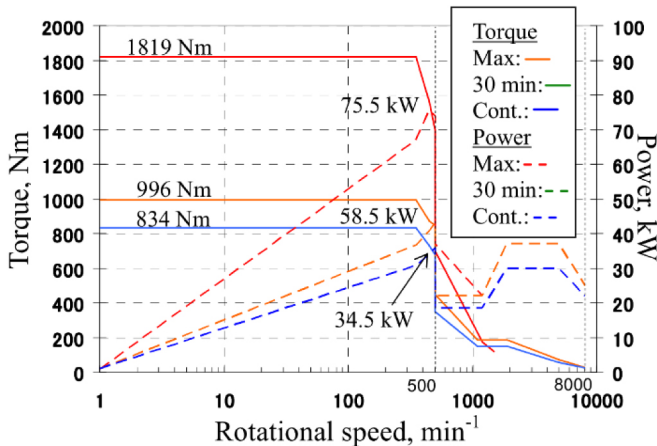


Figure 4. Characteristics curve of DSS.

When designing the DSS prototype, 3D CAD/CAE software has been fully utilized. After developing the virtual prototype by CAD software, the core components were individually analyzed using Finite Element Method (FEM). Then, the system models were also evaluated using the same approach to optimize the design. Figure 5 shows the overview of the DSS virtual prototype. The PMSM was mounted at the end of the original spindle and all necessary mechanisms for the spindle were successfully integrated into the hollow space of the PMSM as shown in Figure 6. The PMSM rotor is supported by inner ball bearings. With the successful integration of the PMSM and other spindle mechanisms, the overall length of DSS is almost the same as that of the original spindle. Therefore, the designed spindle can be simply replaced with the original spindle without any modification to the machine tool structural components. As

introduced earlier, the spindle system has the coupling system, and the high torque and high speed modes can be automatically changed at 500 min^{-1} . For the high torque mode, the rotation of the original induction motor and PMSM can be perfectly synchronized by the CNC controller, whereas the induction motor is only driven for the speed range of $500\text{--}8000 \text{ min}^{-1}$.

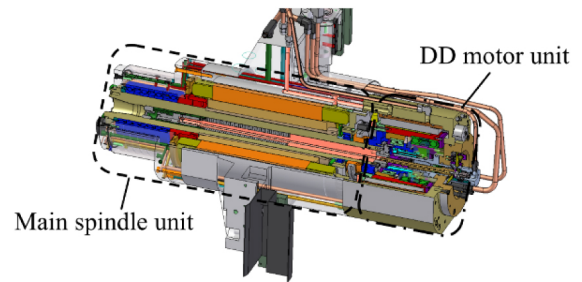


Figure 5. Dual driven spindle virtual model.

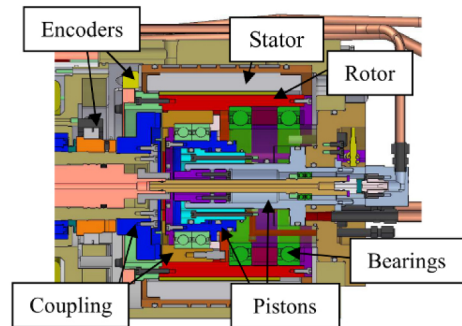


Figure 6. Mechanisms in the PMSM for the DSS.

Prototype Fabrication and Performance Evaluation

After the completion of the virtual models, the physical DSS prototype has been developed as shown in Figure 7. The basic characteristics of the spindle system including static and thermal characteristics have been tested before performing cutting experiments. It was found that there is no significant difference in comparison to the original spindle. The static rotational accuracy was less than 2 Fm at the base of a 300 mm test bar and 5 Fm at the tip of the bar. During high torque operation, the PMSM approaches approximately 38°C , but it was confirmed through experimentation that the generated heat does not affect spindle accuracy.

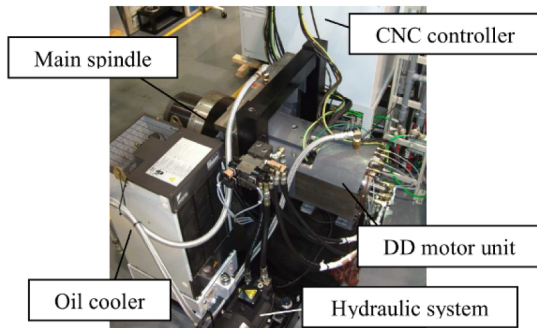


Figure 7. DSS prototype on a test bench.

After the initial tests, the developed spindle system was then installed on a horizontal machining center to investigate the cutting performance of the DSS. Table 1 shows the cutting conditions used for the tests. Cast iron 250 and C55 were chosen for the workpieces. Three different sizes of face milling tools were used for the experiments. Figure 8 shows the maximum Material Removal Rate (MRR) obtained with the cutting conditions. As expected, approximately 2 times higher MRR has been achieved with the DSS in comparison to the original induction motor driven spindle.

Table 1. Cutting conditions for DSS and original spindle.

Work material	Tool diameter	Cutting speed	Feed	Depth of cut
	mm	m/min	mm/tooth	mm
Cast 250	125	196	0.5	6(DSS), 4.5
Cast 250	160	251	0.32	8(DSS), 4
Cast 250	250	250	0.32	5(DSS), 2.5
C55	160	105	0.38	7(DSS), 4

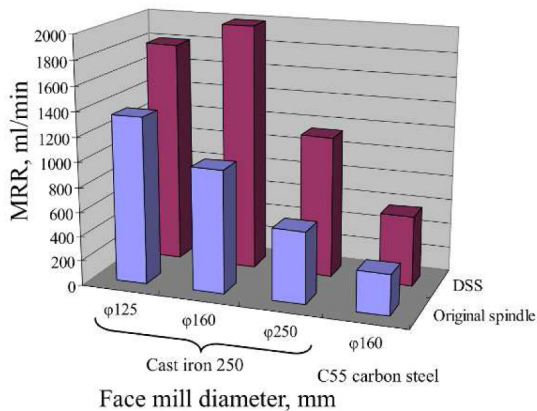


Figure 8. Experimental results by DSS and original spindle.

In addition to the MRR tests, tool wear has been observed for the case where C55 steel has been machined by a 160 mm diameter face milling cutter using the DSS for two different cases where the PMSM is engaged (the DSS ON state) and disengaged (the DSS OFF state). The cutting conditions are:

cutting speed = 251 m/min, feedrate = 1050 m/min (0.3 mm/tooth), depth of cut = 3 mm and width of cut = 100 mm. The insert material was TiCN-Al₂O₃-TiN coated cemented carbide. Also, changes in rotational speeds were measured to observe cutting speed fluctuations. As clearly seen in Figure 9, a remarkable difference in tool wear has been observed between the two cases. In order to find the cause of the tool wear difference, the dynamic characteristics of the spindle in the X, Y and Z directions have been investigated by performing hammering tests. The results are shown in Figures 10,11,12. The slight differences in spindle dynamics seen in Figure 10,11,12 are caused at the coupling for the PMSM motor. Rotational speed fluctuation was also analyzed during machining as the fluctuation indicates the angular vibration of the spindle. While the dynamic characteristics have not shown significant difference in the two states, the magnitude of speed fluctuation at 58.3 Hz, which is the intermittent cutting frequency, was remarkably small as shown in Figure 13 when the DSS is ON as compared to the case where the DSS is OFF. From this fact, it has been found that DSS suppresses rotational speed fluctuation during cutting and results in a dramatic reduction in tool wear.

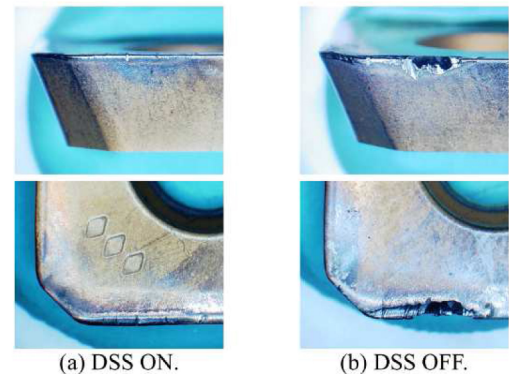


Figure 9. Tools after machining carbon steel C55 with DSS ON and OFF.

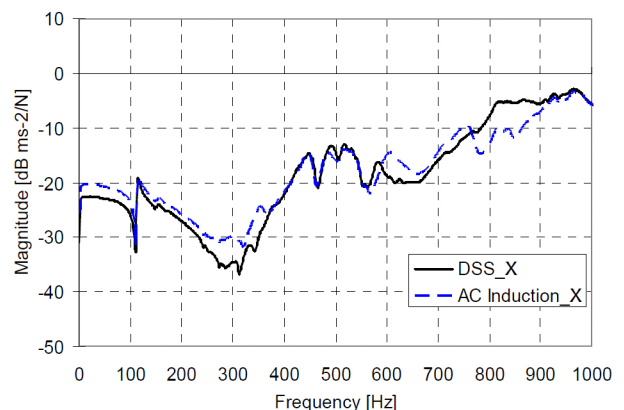


Figure 10. Dynamic characteristics of DSS ON and OFF in X.

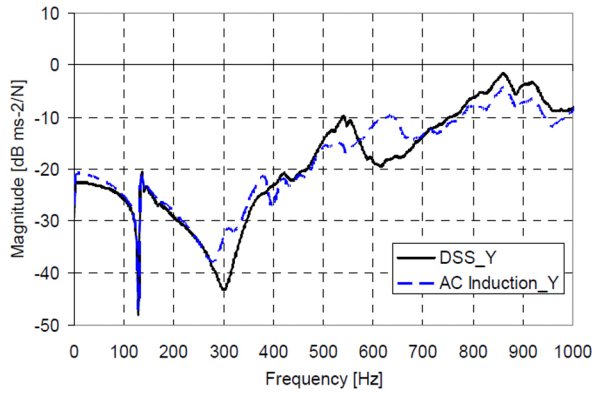


Figure 11. Dynamic characteristics of DSS ON and OFF in Y.

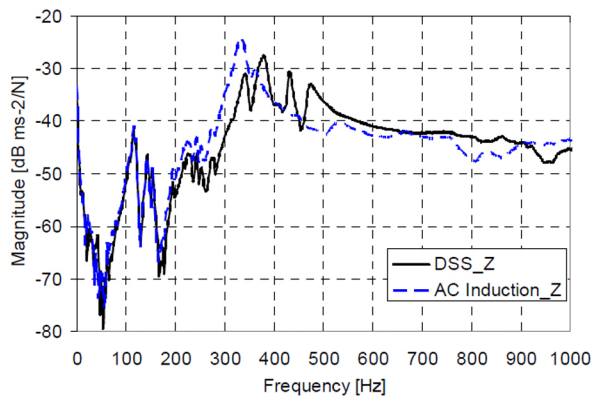


Figure 12. Dynamic characteristics of DSS ON and OFF in Z.

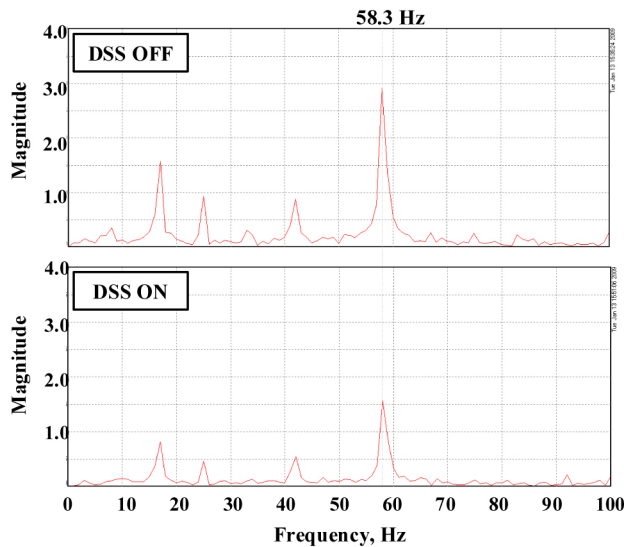


Figure 13. Rotational speed fluctuation during milling.

ANALYTICAL STUDY OF DSS

As demonstrated in the previous section, it was found that the DSS showed preferable characteristics in comparison to the original built-in induction motor spindle. In order to further investigate the dynamic characteristics, especially in the rotational direction, simulation models of the DSS and the original spindle have been constructed and compared.

Construction of Spindle Simulation Models

A block diagram of a typical spindle drive system is shown in Figure 14. To construct a spindle simulation model, the mechanical model, mathematical models of electric motors, and the controller need to be established. For a mechanical system, the electromechanical equation can be expressed as:

$$T - T_L = J \frac{d\omega_m}{dt} + b\omega_m \quad (1)$$

where J is the combined inertia; b is the equivalent viscous friction of the motor and the load; T and T_L are the electromagnetic and opposing load torque, respectively; ω_m is the speed of rotor; and θ is the angular displacement of the rotor.

For the motor models, the well known d-q motor model as shown in Figure 15 is used to describe the working principles of the induction motor and PMSM used for the DSS [2, 3]. Based on the d-q model in Figure 15, the PMSM and electromagnetic torque T can be expressed as the following equations:

$$\begin{cases} V_{ds} = R_s i_{ds} + L_s \frac{di_{ds}}{dt} - L_s i_{qs} \omega_m \\ V_{qs} = R_s i_{qs} + L_s \frac{di_{qs}}{dt} + K_e \omega_m + L_s i_{ds} \omega_m \end{cases}$$

$$T = K_t i_{qs} \quad (2)$$

where L_s is the armature leakage inductance; R_s is the armature winding resistance; K_t is torque constant expressed in units of torque per ampere; K_e is voltage constant expressed in units of voltage per elect. rad/s. The motor q-axis voltage equation for the case the d-axis current is zero becomes:

$$R_s i_{qs} + L_s \frac{di_{qs}}{dt} = V_{qs} - K_e \omega_m \quad (3)$$