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An energy analysis of electric and pneumatic ultra-high speed machine tool spindles

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Abstract

There is a growing demand for ultra-high speed precision machine tool spindles to create complex miniature devices and features, in consumer markets such as medical devices, electronics and communications. The key enabling drive technologies for spindle rotational speeds in the 100,000 rpm range includes electric motors, both AC and DC powered, and air turbines. In particular for high speed micromachining, turbine spindles have advantages in terms of precision and cost. A widely considered drawback of pneumatic technology though is low energy efficiency, but to date there has been little in depth analysis of commercial/state-of-art turbo-spindle energy performance. This paper provides a holistic comparative analysis of electric motor and turbine powered spindle electrical power requirements, by including the power demand of supporting systems and infrastructure. The analysis indicates that at present the energy usage associated with turbine spindles is significantly higher than electric spindles. However, a number of technically feasible energy efficiency measures are identified for turbine spindles, which would make their energy performance comparable with electro-spindles. The analysis and results will contribute towards an overall life cycle assessment of high speed turbo-spindle technology, and provide impetus to further explore energy optimization approaches and methods.

Keywords: Machine Tool Spindles; Energy Efficiency; Micromachining

1. Introduction

Energy usage in machine tools accounts for a large percentage of their environmental impact and operational costs over a lifetime [1]. Therefore there has been considerable research directed towards understanding energy usage [2] and optimizing the efficiency of machine tool components and systems [3], including: spindles [4], feed axes [5], cooling systems [6], coolant supply systems [7], hydraulic systems [8], pneumatic systems [9]. Ultra High Speed (UHS) spindles with rotational speeds in excess of 100,000 rpm are used in the emerging field of meso and micro scale machining e.g. for tool diameters 10 micron to 1mm. To reach such high rotational speeds, both pneumatic and electric powered motors are employed. Given the growing demand for miniature products and features, it is important to understand and optimize energy efficiency of such spindles at an early stage. Previous research has shown that the spindle typically accounts for around 10% of modern automated machine tool energy usage [6]. Furthermore, spindles generally require chilled fluids for reducing thermal distortions, lubricating fluids to reduce frictional losses in bearings and pressurized fluids for tool holding and changing, and sealing. The peripheral equipment such as chillers, pumps, etc., supplying fluids to the spindle often account for a significantly larger portion of machine energy usage. It is therefore important for the scope of the study to consider and include the energy consumption of supporting equipment.

There has been only limited research on the energy efficiency of individual spindles to date [4], and the developments of turbine spindles has focused primarily on achieving very high rotational speeds within a compact volume [10, 11]. There is therefore scope for further research and analysis on the energy optimization of UHS spindles.

1.1. Spindle motors and characteristics

The most commonly used motors in ultra-high speed spindles includes air turbines (turbo-spindle), Alternating Current Induction (IM-AC) and Permanent Magnet Direct Current (PM-DC) motors. UHS spindles typically employ air bearings (often referred to as air spindles in the literature) or hybrid rolling element bearings. It is important to note that while both turbine and electro-spindles are commercially available with similar speed capacities, they generally have different power output and dynamic runout ratings, which makes a direct comparison difficult.

The non-linear torque-speed characteristics of AC induction motors at a constant supply frequency, are well documented in the literature. Fig 1 therefore illustrates the characteristic curves for turbine and PMDC motors, and some important distinctions are evident. Firstly, air turbines and air motors in general, are sized to operate at maximum mechanical power output, which occurs at approximately half the free/no load speed of the motor. The turbine achieves maximum efficiency at maximum power. In contrast, DC motors (and AC motors) are selected to operate closer to their maximum operational speed with lower output power for optimal efficiency. Typically electric motors can operate at maximum output power for only limited periods, with the duty cycle based on thermal considerations. In addition, there is a high current inrush when starting electric motors (Fig 1).
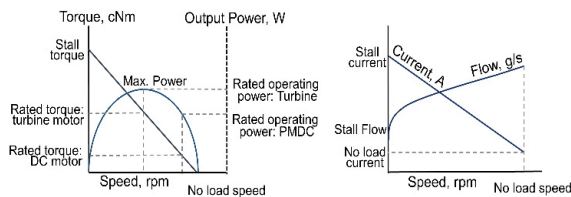

Fig. 1. Characteristic curves for PMDC and turbine motors, at constant supply pressure or applied voltage.

From an energy consumption point of view, it is interesting to note the different trajectories of electrical current and compressed air mass flow during loading (Fig 1). At a low/no torque load conditions, turbine motors will operate at higher speed and flow demand, if ungoverned. Lower cost turbine spindles (e.g. hand operated power tools) without speed control therefore consume a maximum amount of energy when idle, with flow demand decreasing during cutting. This is in contrast to the familiar current draw during electric spindle operation. For both electric and pneumatic technologies, there is an energy flow in the form of compressed air or electrical current at stall.

High speed spindles for machine tools generally require control systems to maintain a consistent rotational velocity during machining, and to adjust the cutting speed as required by different machining processes. Fig 2 illustrates the adaption to the characteristic curves for IM-AC motors with adjustable frequency drives, and turbine motors with variable pressure and flow control systems. The regulation of pressure and/or flow rate with proportional electropneumatic valves allows for efficient part load operation of turbine spindles (Fig 2). Alternatively, some commercial turbo-spindles have centrifugal governor mechanisms to limit speed, and which typically also reduce idle compressed air demand to below working (loaded) demand.
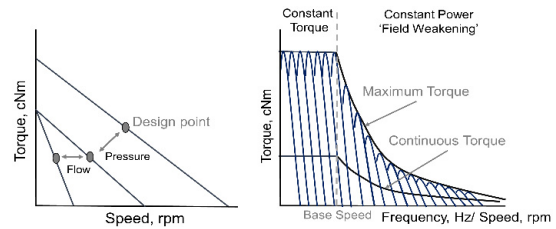

Fig. 2. Control methods for turbine (left) and IM-AC motors (right).

2. Scope and boundaries for energy study

In comparing spindles with different energy sources, it is necessary to expand the scope of the study to account for the ultimate electrical energy consumers (Fig 3). In most industrial facilities, pneumatic devices such as turbine spindles, are supplied by an electrically powered air compressor. Additional energy in the form of electricity or compressed air will be consumed in the treatment of the compressed air e.g. drying. While UHS electro-spindles do not require a supply of compressed air for the motor, they do require cooling systems to reduce thermal distortions. It is also necessary to consider the effect of spindle weight on the power requirements of supporting feed drives, to account for any power-to-weight advantages of either drive technology. Finally, the expansion of compressed air in the turbine of a spindle results in a reduction in temperature of exhaust air exiting the turbo-spindle. In fact, the same principle underlies the expansion turbines of 'Air Cycle Machines' which are widely used to provide refrigeration on aircraft and trains. Given that recent research has shown the chilled air can be used effectively for cooling and chip removal in micromachining processes [12], it is therefore interesting to assess the utilization of cold air exhaust from turbine spindles on overall energy usage also. The utilization of refrigerated air as coolant is also beneficial, as the post-cleaning of excess lubricant fluid of miniature parts is difficult [13].

Other energy consumers such as hydraulic and lubrication pumps, and controllers, are considered outside the scope as they can apply to both turbine and electro-spindles i.e. the bearings for the turbine and electric spindle comparison are considered the same.
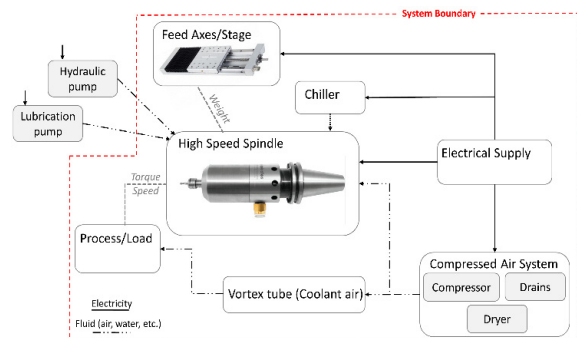

Fig. 3. System boundaries for energy analysis of UHS spindles.

3. Theoretical peak power assessment

A survey of commercial UHS spindles indicated that there are no overlapping spindles, in terms of power and speed, currently available on the market. Therefore, in order to estimate the electrical power requirements of both technologies, a hypothetical case was developed for a spindle with 300W maximum mechanical power output at a working speed of 100,000 rpm.

The assumed efficiency values for each system are shown in table 1, and are based on data taken from manufacturers' datasheets, international standards, literature review and previous industrial case studies. The manufacturers of electro-spindles do not typically provide energy efficiency information, therefore the efficiency of the spindle motor is estimated based on the latest IE3 standard for AC induction motors.

The simplified air power approach [14] is used to determine the efficiency of the turbine spindle based on the specified work output and air flow requirements. However, in order to fully compare electric and pneumatic technology, it is important to consider the electrical power requirements of the supporting Compressed Air System (CAS). A brief overview of exergy efficiency definitions for compressed air systems is given in [15]. For both electric and turbine spindles, the efficiency is at maximum when operated at rated conditions.

The power-to-weight ratios are also based on spindle manufacturer data. A survey of commercially available electric and turbine spindles indicated little difference between power-to-weight ratios at present. This is in contrast to other industries, where (air) turbine driven dental drills and angle grinders, achieve significantly better power-to-weight performance.

Table 1. Rated efficiency and power-to-weight values for spindle and support systems

Efficiency	Typical range	Selected
Electric Spindle, Exergy %	60 - 90	80
Turbine Spindle, Exergy %	5 - 30	20 & 60
Compressed air system, Exergy %	20 - 60	40
Chiller COP	0.5-3	1.5
Vortex tube COP	0.05-0.2	0.2
Power-to-Weight ratio		
Electric Spindle, kW/kg	0.05-0.5	0.15
Turbine Spindle, kW/kg	0.05-0.5	0.15 & 0.8

The chiller supplying cooling water to the electric spindle is sized based on the maximum heat transfer requirements of the spindle i.e. to supply enough cooling power if the spindle is operating at high load/low efficiency. Its Coefficient of Performance (COP) is based on the typical performance of small air cooled vapor compression chillers [16].

Based on the efficiency values in table 1, the estimated electrical power requirements for a fully loaded turbine and electric spindle are shown in Fig 4, and clearly indicate that electric spindles offer better performance from an energy efficiency perspective, at present. The peak power requirements of a compressed air system supplying the turbine spindle is approximately six times that required for the electric spindle with chiller. This is mainly due to the low efficiency of commercially available turbine spindles.
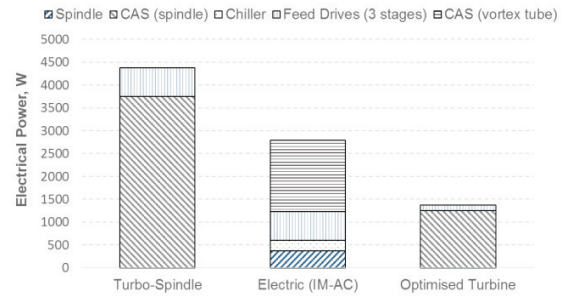

Fig. 4. Maximum electrical power demand for 300W spindle and systems.

4. Opportunities for improved turbo-spindle efficiency

Given the competitive advantages in terms of precision and initial costs, it is desirable to improve the energy efficiency of turbo-spindle technology further. For that reason, also included in Fig 4 (in the bar furthest to the right), is the potential peak power requirements with a turbine spindle optimized for both weight and energy efficiency.

4.1. Energy savings with optimized turbine

An advantage of turbine motors in comparison to other pneumatic motor technology is high efficiency, in particular for conventional turbomachinery applications. For example, isentropic efficiencies of 85% are considered achievable for expansion turbines in air cycle machines [17]. However it is important to note that efficiency scales with size, and it is difficult to attain the same level of performance for miniature turbines. Therefore in order to account for the relatively small power output of UHS spindles, an optimized exergy efficiency value of 60% is assumed for the turbine spindle, based on latest research on microturbine technology [18, 19]. This is equivalent to an isentropic efficiency of approximately 65% at a pressure ratio of 3.

4.2. Energy savings with feed drive payload reduction

Turbine powered hand-held grinders with power-to-weight ratios of over 1.1 kW/kg have been reported in the literature [20]. With improvements in turbine efficiency and reduced spindle component weight, an optimized value of 0.8 kW/kg is therefore deemed plausible.

In order to account for power and energy savings, due to reduced payload on the machine tool feed drive/s that position the spindle, a typical feed axis configuration is assumed (table 2). Typically, in cases where cutting forces are small or negligible e.g. micromachining, feed drives are sized to allow for a rapid traverse of full stroke length. To reach a typical rapid traverse velocity of 2.5 m/s, within the 200mm travel requires a high acceleration rate. Given the linear relationship between the peak force required by the feed motor and spindle payload, a significant reduction in payload leads to a corresponding equivalent reduction in peak force and therefore electrical power requirements.

Note, the additional payload masses of cables and slides were omitted from the analysis. The feed drive in this study is sized based on a trapezoidal velocity motion profile (Fig 5). For simplicity a constant friction force is assumed, and

the power demand for multiple stages is estimated to increase linearly i.e. if operated simultaneously. The assumption of a trapezoidal velocity profile likely underestimates actual feed motor power requirements, as most machine tools use jerk limiting motion profiles e.g. S-curve, with higher peak power requirements. In addition, linear motor stages are often supplied by cooling systems [21], which are also not considered.

Table 2. Feed drive parameters for energy study

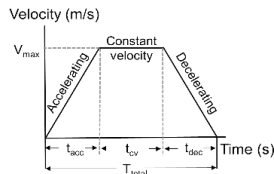|	
Axis length, mm	200
Max. velocity, m/s	2.5
Max. Acceleration, m/s^2	30
Friction, % of Peak Force	5
Linear motor efficiency, %	65
Number of stages	3

Fig. 5. Trapezoidal motion profile for linear feed drive.

Fig 4 indicates that an optimized turbo-spindle system, with an exergy efficiency of 60% and a power-to-weight ratio of 0.8 kW/kg, could offer comparable energy performance to that of an electric spindle, given the small difference in power requirements.

4.3. Energy savings with chilled air utilization

A further opportunity for energy savings, assuming that machining with chilled air has been found effective for the process, is to utilize the cold air exhaust from the turbine spindle as coolant. The cooling capacity, $\dot{Q}$ (W), of a turbine-spindle is calculated using equation 1, where $\dot{m}$ is mass flow (kg/s), C_p is specific heat capacity (kJ/kg.K) and ΔT is the temperature difference (K).

$$\dot{Q} = \dot{m}.C_p.\Delta T \qquad (1)$$

At present vortex tubes are widely used in industry for producing a cold air stream from compressed air, but are relatively inefficient refrigeration devices [22]. The electrical power requirements of an air compressor supplying a vortex tube, with cooling capacity equivalent to the turbine spindles i.e. approximately 300W, is therefore also shown in Fig 4.

The figure demonstrates the potential energy savings by using a turbine spindle for both power transmission and process cooling purposes. If used in this manner the turbine spindle would eliminate or reduce the coolant system requirements for the machine tool, though clearly the potential utilization of cold air exhaust will be restricted to a certain extent by heat generation in the bearings.

4.4. Energy savings with elimination of sealing air

Finally, it is worth highlighting that many electro-spindles use compressed air for sealing purposes, to protect the spindle and bearings from chips and particles [4]. Including the power demand for an air compressor supplying

the sealing air, would further increase the overall electrical power requirements of the electro-spindle and its support systems. Compressed air for sealing purposes in turbo-spindles is unnecessary, due to the positive air pressure in the housing.

5. Theoretical part-load power assessment

5.1. Spindle dimensioning

There is high uncertainty in the dimensioning of a spindle for a specific machining process. Fig 6 shows the required cutting power for slot milling of an aluminum alloy with two different cutting speeds (V$_c$). In particular for micromachining, the large variation in predicted specific cutting pressure (K$_c$) may also result in spindle oversizing in order to ensure adequate power for cutting - in the case of potential higher cutting force requirements. Moreover, the feed rate and therefore required cutting power is also limited by the fragility of microtools. In order to avoid breakage of expensive miniature tools, conservative feed rates are often applied at present [23].

Fig 6 indicates that, even considering frictional power losses, a 300W spindle is likely operated at low loads during material removal operations. In fact, given that commercial spindle motors are typically oversized to allow for rapid acceleration/deceleration and reduced run-up times [4], it is likely that most UHS spindles are operated at part-load even during relatively rough cutting. However, the efficiency of all motor types (DC, AC and turbines) deteriorates at low load and low speed conditions, with the drop in efficiency more pronounced for smaller motors.
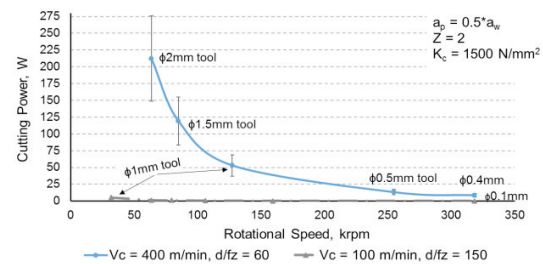
Fig. 6. Cutting power requirements for milling aluminium alloy, where a$_p$ = axial depth of cut, a$_w$ = radial depth of cut, Z = number of flutes.

5.2. Partial-load power demands

It is therefore important to consider the power demand of the spindle(s) and their supporting components under the most frequent machine tool states, e.g., machine ready, idle, positioning and cutting. An example of a typical spindle duty cycle is shown in [4]. The transient acceleration of the spindle is neglected in this analysis, given that the energy usage due for acceleration of spindles is generally small [24]. The required mechanical power output from the spindle, and the fraction of Full Load Power (FLP) output is shown in table 3. The cutting power is based on Fig 6. The frictional power loss of angular contact ball bearings at 100,000 rpm is estimated based on the simple Coulomb friction torque model i.e. with a constant coefficient of friction. Nevertheless, the fraction of frictional power loss is in line with other publications [4, 18].

In order to estimate the electrical power demand of the spindle motors at part-load, it is also necessary to estimate their efficiency (table 3). The reduction in efficiency of a variable speed IM-AC motor from its optimal value is estimated based on the results in [25] for a 4kW, 1500 rpm motor i.e. the drop in efficiency at an equivalent torque load is assumed the same. Similarly, the reduction in efficiency of the (optimized) turbine is based on the part-load results in [18] for a 170W, 495,000 rpm motor.

Table 3. Estimated loading, efficiency at part-load and electrical/air power requirements for 300W spindle at main operating states

	Unit	Ready	Idle	Cutting
Rotational speed	rpm	0	100,000	100,000
Power output	W	0	10	90
Fraction of FLP output	%	0	3	30
Turbine motor (optimal)				
Efficiency reduction [18]	%	-	0.3	0.15
Part-load efficiency	%	0	0.3	0.45
Air power	W	0	33	200
Electric Motor				
Efficiency reduction [25]	%	-	0.5	0.2
Part load efficiency	%	0	0.3	0.6
Electrical power	W	3.75	33	150

The estimated power demand of the spindle support systems associated, with the major machine states, is shown in table 4. It is interesting to note that the energy efficiency of chillers in part load is very low and results in significant consumption of energy when idle [16]. In addition it has been found for chillers with hot gas bypass control, that there is little variation in electrical power at low loads i.e. the power demand is nearly independent of machine condition [6]. The idle power demand of rotary screw air compressors is approximately 20% of full load power demand [26]. Air compressors with variable frequency drives can reduce motor speed to meet reductions in air flow demand, and can maintain a relatively stable efficiency when operated between 40 and 85% of full capacity [26]. The air compressor supplying a vortex tube is downsized to account for the low mechanical power and therefore expected level of heat generation. The required cooling capacity is assumed to be 100W during cutting.

The electrical power demand of the feed drives is not considered at part-load, as they require only a fraction of their rated electrical power during steady state e.g. cutting, and the difference in power demand due to payload (spindle) reductions is negligible.

Table 4. Estimated support system power requirements in part-load

Consumer	Spindle State	Fraction of FLP, %	Electrical Power, W
Chiller	Ready	80	180
(Electric)	Idle	80	180
	Cutting	85	203
Air compressor	Ready	20	250
(Optimized Turbine)	Idle	20	250
	Cutting	40	500
Air compressor	Ready	20	100
(Vortex tube)	Idle	20	100
	Cutting	100	500

The electrical power demand of a 300W spindle and its support systems under partial load are shown in Fig 7. The results again indicate that performance of pneumatic and electric driven spindle technologies could be comparable from an energy efficiency perspective. Crucially, this comparison depends on the development of turbine spindles optimized for efficiency, weight and exhaust air utilization.
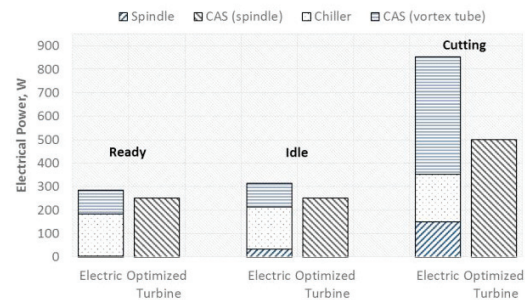

Fig. 7. Electrical power demand of 300W spindle and support systems in part-load conditions.

6. Discussion and research outlook

6.1. Energy usage modelling

The ultimate electrical energy usage of the spindle and its support systems depend on the uptime of the machine tool and its utilization. A typical breakdown of machine states from [27] is 60% cutting, 30% positioning (spindle is in idle state) and 10% idle time (spindle is in ready state) with a machine uptime of 4,000 hours. The breakdown is based on the assumption that to justify a capital intensive purchase, the production machine must process a sufficient amount of materials, and therefore the machine should have a low amount of idle time [27]. Based on the prior assumptions, the approximate annual electrical energy usage of electro-spindle and optimized turbo-spindle, with their support equipment, is 2,300 kWh and 1,500 kWh respectively.

However, given the short life of miniature tool bits, and therefore increased frequency of tool changes, it may be important to include the energy usage due to spindle acceleration in the analysis. This is particularly important for commercial UHS spindles e.g. in PCB drilling, where a significant time is often required for tool changing. The modelling approach proposed in [24] for example may provide for a more accurate energy usage assessment for future work.

6.2 Efficiency Measurement /Mapping

The preceding sections have highlighted the importance of understanding the efficiency of ultra-high speed motors at part load, but this is currently lacking in the literature. In order to fully understand and verify the energy efficiency of UHS spindles, it is necessary to experimentally measure power and flow demand under different loading conditions. To date, there have been only limited measurements of spindle power demand and energy efficiency specifically. Instead, spindle power data is often aggregated with other energy consumers on a machine tool. Moreover it is challenging, in particular for turbo-spindles, to measure the relatively low mechanical torque output at high rotational speeds, and at present few commercial solutions exist. This problem is shared with small turbochargers, and typically highly expensive and

customized dynamometers have been developed in the past [28]. In general, for high speed spindles with AC-IM motors, the efficiency maps (Fig 8) proposed for electric vehicles [25] may provide a useful template for future spindle performance comparisons at part-load.
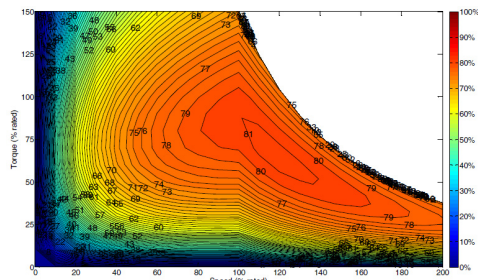

Fig. 8. Sample efficiency map for 4kW, 1500 rpm, variable speed AC induction motor [25].

7. Conclusions and future work

In this paper the energy efficiency of turbine and electric motor driven ultra-high speed spindles is investigated. A holistic approach is taken, whereby the electrical power requirements for both types of spindles, and their supporting systems is considered. At present, the power demand attributed to a turbine spindle is considerably higher than that for an equivalent rated electric spindle. Clearly however, from a competitive economic or environmental standpoint, energy usage is only one factor in a spindle's life cycle cost or impact.

Given some of the non-energy related advantages of turbine spindles for ultra-high speed micromachining, a number of energy efficiency measures have been proposed, that have the potential to equalize overall electrical power demand of the spindles and their support systems. In particular, the importance of part-load efficiency, a low inertia motor, and the utilization of exhaust air from the turbine have been highlighted. In order to assess and verify the proposed energy efficiency measures, future work is concerned with the design and development of an energy optimized UHS turbine spindle.

Acknowledgements

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