

# EFFECTS OF ACTIVE BALANCING ON HIGH-SPEED MILLING PRECISION

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## ABSTRACT

High-speed machining processes can be very sensitive to variables not necessarily important at lower cutting speeds. Unbalanced toolholders and spindles, for example can generate forces at high-speed that cause significant dynamic error motion of the cutting tool.

Experimental results are presented here that show how spindle-housing vibration can be minimized at each operating speed using active mass balancing. The relationship between unbalance and dynamic tool runout is quantified for a common type of machining center. Unbalance-induced runout is shown to contribute to dimensional errors and cutting instability in end milling by increasing the effective radial depth of cut. Theoretical analyses of milling cutter kinematics show that eliminating unbalance-induced runout through active balancing can improve surface finish for cases in which static runout is very small.

## INTRODUCTION

Because unbalance forces are proportional to the square of the rotational speed, these forces can be the same order of magnitude as high-speed cutting loads. Since ball bearing fatigue life is known to be inversely proportional to the cube of the effective bearing load (Harris, 1991), the presence of even moderate unbalance loads can potentially reduce spindle life. Unbalance forces also excite the spindle and support structure, leading to tool error motion.

To minimize unbalance forces, tool/toolholder combinations for high-speed machining are often balanced "off-line" prior to insertion into the spindle. Even using balanced tools, however, the spindle/toolholder rotating assembly can still exhibit significant unbalance variation after each tool change due to the combination of residual unbalance in the spindle itself, toolholder clamping tolerances and clearances in the clamping and drawbar assembly.

To balance the tool/spindle assembly after each tool change would significantly increase cycle-time and not typically be cost-effective. Furthermore, a

single-plane balance at the toolholder at one speed may not be suitable at another speed because of the potential for unbalance located in the drawbar or toward the rear of the spindle. To thoroughly compensate for such a situation one would need to perform multiple-plane balancing. Another approach is to utilize single-plane active balancing to minimize unbalance-induced vibration at the desired spindle operating speed.

To eliminate the potential harmful effects of increased spindle loads and error motion, an active balancing device was developed (Dyer et al., 1998) that can adjust toolholder balance while the spindle rotates at operating speed. Mass balance compensation can, therefore, take place rapidly after each tool change prior to metal cutting. The effect of such on-line balancing was quantified using several measures of machining precision.

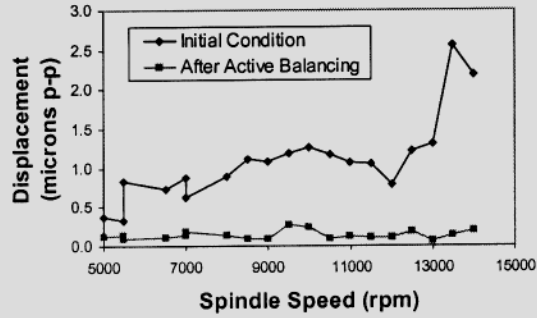
## ACTIVE BALANCING TO MINIMIZE HOUSING SPINDLE MOTION

Tests were performed on a horizontal machining center to measure the vibration induced by residual spindle/toolholder assembly unbalance after inserting a balanced toolholder. The vibration was then minimized at each spindle speed up to the maximum 14,000 rpm operating speed. The resulting spindle housing vibration before and after active balancing is shown in Figure 1.

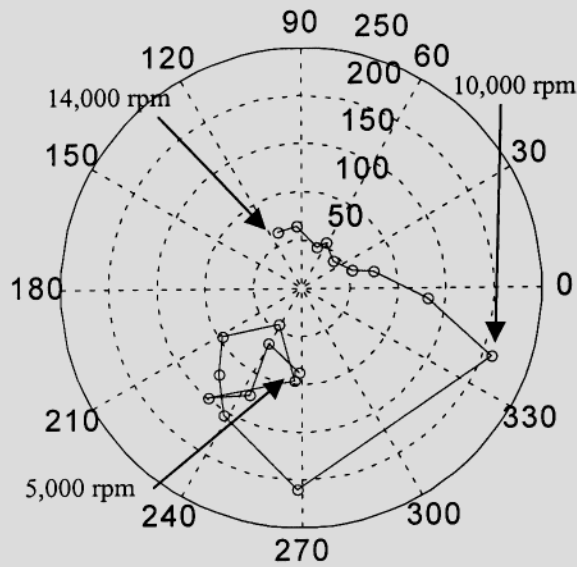
Figure 1 shows that active balancing was successful at maintaining low vibration levels regardless of the spindle speed. However, the balance correction magnitude and phase angle required to minimize vibration varied dramatically with spindle speed. Figure 2 shows the optimal balance correction phasor (magnitude and phase angle) to minimize dynamic spindle motion at different speeds through the operating speed range.

At 10,000 rpm about 200 g-mm at 340° was required. At top speed of 14,000 rpm, 30 g-mm at 120° was the best correction. If one were to manually fix the balance at one speed, therefore, the

unbalance and resulting vibration at another speed may in some cases actually be worse than with no balance correction at all. Active balancing in this case allowed rapid balance corrections to minimize spindle motion at the exact cutting speed.



**Figure 1. Horizontal Machining Center Spindle Housing Vibration Before and After Balancing With Balanced Toolholder**

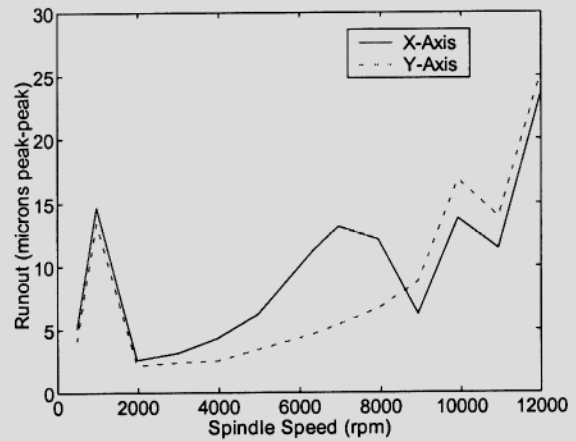


**Figure 2. Horizontal Machining Center Effective Single Plane Unbalance (g-mm) for Various Spindle Speeds**

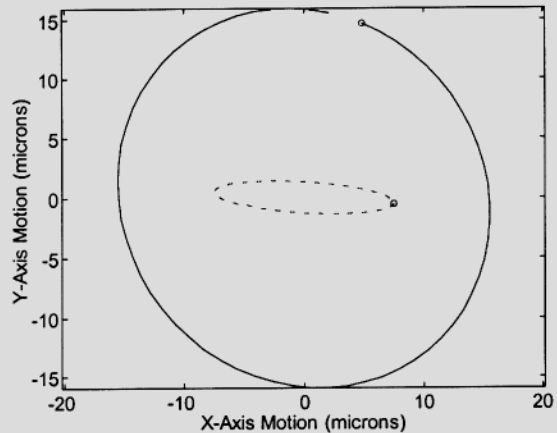
**EFFECT OF UNBALANCE ON DYNAMIC TOOL RUNOUT**

As seen from the above results, unbalance forces cause dynamic error motion in the machining spindle that can vary after each tool change. The dynamic tool runout combines with the static runout to make the tool diameter effectively larger (or smaller) depending on how the two runout vectors add together.

The effect of unbalance on tool runout was measured for a vertical machining center with a 40 taper toolholder. An active balancing device mounted on the toolholder was used to adjust balance at various speeds to minimize spindle housing motion (measured using accelerometers in two axes at the spindle nose). The motion of a gage tool was measured using capacitance probes in two orthogonal radial directions. The active balancing device was then used to adjust the unbalance to a known amount and the tool motion again measured. Figure 3 shows the magnitude of the change of spindle-synchronous runout caused by a 210 g-mm unbalance at the toolholder.



**Figure 3. Measured Change in Spindle-Synchronous Tool Runout Caused by 210 g-mm Unbalance at Various Spindle Speeds**



**Figure 4. Measured Tool Motion With Toolholder/Spindle Assembly Balanced and Unbalanced 210 g-mm at 12,000 rpm**

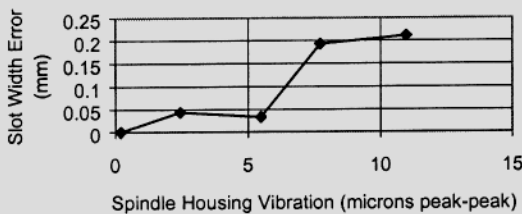
Capacitance probe system sampling rate limitations did not allow measurements above 12,000 rpm even though the spindle was capable of

operating up to 15,000 rpm. The greatest change in runout in the measurement range was effected at 12,000 rpm. Figure 4 shows the spindle-synchronous tool orbits in the balanced and unbalanced condition at 12,000 rpm.

### EFFECT OF UNBALANCE-INDUCED DYNAMIC TOOL RUNOUT ON END MILLING DIMENSIONAL ACCURACY

As shown by the results above, unbalance can cause tool runout. Researchers have in the past shown that runout causes one flute to do more cutting than the rest, leading to larger variation in cutting loads from one flute to the next (Kline and DeVor, 1983). Thus unbalance-induced runout could, therefore, contribute to premature wear of a single cutter flute. Another effect of this runout is to increase the radial depth of cut unintentionally. This can lead to dimensional errors in the workpiece.

This effect was measured for a representative process. Slots were milled in extruded aluminum using a two-flute, 19 mm diameter cutter at 16,000 rpm. Each slot was milled under conditions of different amounts of unbalance-induced spindle housing vibration. A machine will exhibit different sensitivities to unbalance at various speeds for various tools. Therefore, the critical parameter for predicting machining inaccuracies is not necessarily unbalance, but rather the error motion caused by unbalance at a given speed. Figure 5 shows the effect of such unbalance-induced spindle-housing vibration on slot width accuracy. The maximum vibration of about 11 microns corresponds to about 300 g-mm unbalance for the spindle at the given speed.

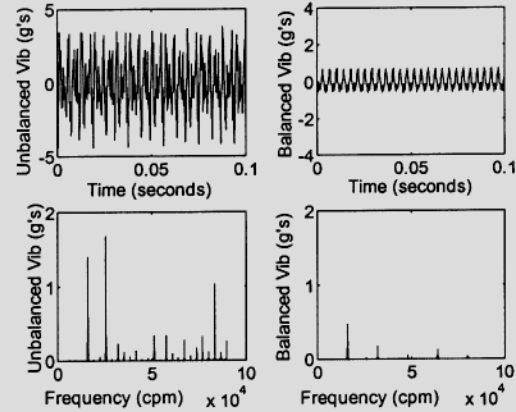


**Figure 5. Milled Slot Width Error vs. Unbalance-Induced Spindle Housing Vibration (16,000 rpm, 19 mm, 2-flute cutter, 0.1524 mm feed/rev)**

### EFFECT OF UNBALANCE-INDUCED RUNOUT ON MACHINING STABILITY

As discussed above, unbalance can induce significant tool runout that effectively increases the cutter diameter and radial depth of cut. Increasing the radial depth of cut in this way can have a detrimental effect on milling stability margin. Figure

6 shows the spindle housing vibration during an unstable cut (on the left) compared to the stable cut (on the right) achieved by balancing the spindle at the same operating conditions.



**Figure 6. Measured Spindle Housing Vibration During Unbalanced and Balanced Slotting Cut (19 mm 2-flute cutter, 1.4 mm axial depth of cut, 0.1524 mm feed/rev, 16,000 rpm)**

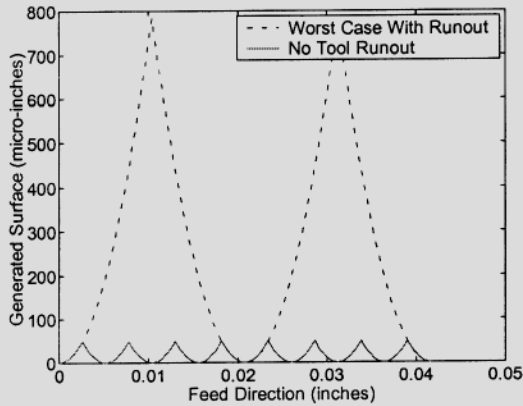
The vibration spectrum on the left of Figure 6 from the unbalanced cut displays not only higher spindle-frequency vibration at 16,000 cpm, but also vibration at a chatter frequency at 25,200 cpm. Such unbalance-induced machining instability would only be expected to occur if one were operating very close to the stability limit and, therefore, is not in itself a tremendously significant issue. However, it is another indication of the significant dynamic runout caused by unbalance.

### EFFECT OF UNBALANCE ON MACHINING SURFACE FINISH

As other researchers have noted, tool runout can effect the surface waviness generated during end-milling (Liang et al., 1993). In the best scenario of no tool runout, all the flutes contribute equally to generating the surface profile. If enough runout is present, only one flute will act to generate the surface and the other flutes do not contact the generated surface. The amount of tool runout present will determine whether something approaching the best surface profile is achieved (generated by all flutes in the cutter) or the worst surface profile is achieved (generated by only one cutter flute). An example of surfaces generated using a four-flute cutter with and without runout is shown in Figure 7. The idealized surfaces shown were predicted using simple kinematic simulation, assuming perfectly sharp cutting edges and neglecting tool flexibility.

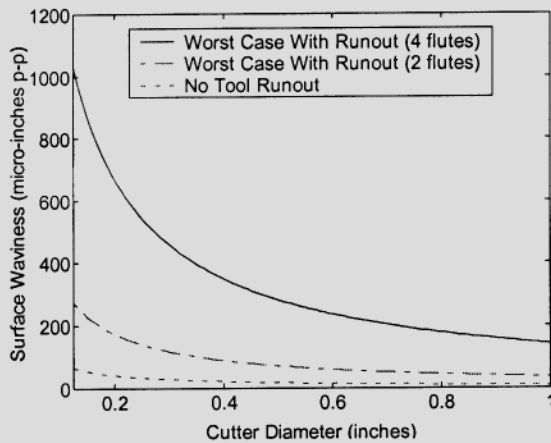
As runout increases, the idealized generated machined surface would change from the solid lower

surface to become more like the upper dashed surface. When the runout reached a certain level only one cutting point would be effective and the machined surface will correspond to that of a single-point cutting process.



**Figure 7. Predicted End-Milled Surfaces: 0.125 Inch, 4 Flute Cutter, 0.0052 Inch Feed/tooth**

Interestingly, if the runout increases beyond this level, the surface will not change because the effective number of cutting flutes is still one. (Although the location of the surface will exhibit dimensional error as noted previously). Thus the “worst case” surface generated will correspond to that of a single-point cutter of the same diameter. Figure 8 shows, for a fixed feed-per-tooth, the best-case (no tool runout) and worst-case surface waviness for two and four flute cutters of varying diameters. The surface profiles predicted in Figure 8 were based on the same kinematic assumptions as for Figure 7.



**Figure 8. Predicted Surface Waviness on Upcut (0.006 Inch Feed/tooth)**

It can be noted from Figure 8 that the difference between the worst- and best-case surface waviness increases as the number of flutes increases and as the cutter diameter decreases (for a fixed feed).

If static tool runout is very small, eliminating the unbalance-induced runout will enhance surface profile by ensuring that all cutter flutes participate in generating the milled surface instead of just one. If the static tool runout exceeds a given value, however, eliminating unbalance will not effect surface waviness because the surface will still be generated by only one cutting point.

## SUMMARY AND CONCLUSIONS

Unbalance forces can be significant contributors to overall spindle loads for high-speed milling. Aside from potentially limiting spindle bearing life, unbalance loads also cause dynamic tool runout. The amount of runout for a given unbalance depends on the machine sensitivity to unbalance at the specific spindle speed. Because runout increases the effective cutter diameter and radial depth of cut, unbalance can lead to significant milling dimensional inaccuracies. Balancing can also theoretically extend tool life and improve surface waviness by helping to ensure that all cutter flutes engage equally in the cut. Balancing the tool/spindle assembly on the machine helps ensure optimal processes even with tool clamping misalignment and unbalanced spindles. Active balancing provides the potential to cost-effectively perform such on-machine balancing. Active balancing is thus a means for eliminating a significant process variable, resulting in enhanced precision, reliability and productivity.

## REFERENCES

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