THE EFFECT OF NON-UNIFORM INSERT PITCH ON NOISE GENERATION DURING FACE MILLING OPERATIONS

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ABSTRACT

Excessive noise generation often occurs during the face milling of certain thin-walled aluminum workpieces. Theoretically such noise can be reduced by utilizing milling cutters which employ non-uniform insert pitch. This study reports on the results of a series of tests undertaken to determine the noise reduction potential of four different non-uniform pitch cutters used to machine the engine mounting face of an aluminum transmission housing. It is shown that the use of non-uniform insert pitch does not necessarily reduce overall noise generation. There is, however, often a reduction in "noisiness". The difficulties of applying existing "quiet" cutter design principles to workpieces of complex geometry are also discussed.

SOMMAIRE

Très souvent, lors de l'usinage en plan de certaines pièces d'aluminium de faible épaisseur, un niveau de bruit excessif est constaté. Théoriquement, ce bruit peut être atténué par l'utilization de fraises dont les couteaux sont répartis de manière non-uniforme sur la périphérie. La présente étude rend compte des résultats obtenus lors d'une série d'expérimentations menées afin de déterminer la capacité réductrice de bruit de quatre différentes fraises à répartition non-uniforme. Ces fraises ont été testées lors de l'usinage de la surface d'assemblage avec le moteur du carter d'une transmission. Ces expérimentations ont permis de constater que l'utilization de fraises à répartition non-uniforme ne réduit pas forcément le bruit généré. Toutefois, on remarque que le caractère "gênant" due bruit est souvent atténué sensiblement. Ajoutons que l'étude a aussi porté sur les difficultés rencontrées lors de l'application des principes de conception de ces outils "silencieux" à l'usinage de pièces de géométrie complexe.

INTRODUCTION

In recent years significant progress has been made in reducing noise levels generated during the operation of high volume, multistation transfer machines. Generally, these reductions have resulted from the demands of purchasers who must meet government legislated limits and who also wish to avoid the economic penalties associated with claims for hearing damage compensation. Yet, in spite of these improvements, there still exists the need for further decreases in machine noise levels.

Transfer machines consist of many automatic machine tools which are interconnected by a central transfer spine. The workpieces, generally mounted on pallets, which act as the machining fixtures, are moved sequentially from one tool, or "station", to the next. This process is intended to meet high production requirements and, as such, is used extensively in the transportation industry.

The relatively recent thrust made by the transportation industry toward lighter, more fuel efficient vehicles, has meant that the machine tool industry must often machine thin-walled, light-weight castings on high-volume, transfer-lines. In addition, the need to reduce unit costs has led to demands for substantially increased production rates.

Thus, manufacturers of transfer lines are presently confronted with the need to produce machines which cut more metal faster, from relatively more compliant parts, than has previously been the case. Unfortunately, this often results in the generation of excessive noise levels during the machining cycle. In the particular case of aluminum transmission housings, the combination of high cutting speeds, thin walls and bell-like geometry can result in excessive noise generation during the face milling process. Sound levels as high as 118 dBA have been measured at a distance of 3 m from actual production machinery. The generation of such noise levels makes it extremely difficult for manufacturers to meet existing occupational noise exposure limits. The fact that many jurisdictions are presently contemplating a further tightening of noise regulations, will only compound these difficulties. If machines cannot be produced to meet present and future noise limits, then both machine tool users and builders are likely to suffer significant economic penalties.

Face milling is a very common machining process during which a flat surface is generated progressively by the removal of small amounts of material ("chips") as the rotating milling cutter is fed across the stationary workpiece. It is, of course, possible to move the workpiece under a stationary milling cutter, however this is normally not done on transfer machines due to fixturing restrictions.

In all practical cases, multiple-tooth cutters are used to provide high metal removal rates. Often the desired surface may be obtained in a single pass of the cutter and since excellent surface finish can be obtained, face milling is particularly well suited, and widely used, for mass production machining systems.

The face milling cutter itself consists of a cylindrical, steel body containing cutting inserts ("teeth") which intermittently engage and cut the workpiece. See Figure 1. Most commonly, the inserts are evenly spaced around the periphery of the cutter body. Their orientation means that the cutting action occurs on both the periphery and "face" of the milling cutter. It is for this reason that the process is known as face milling. The inserts are usually made from carbide or ceramic materials. In most high volume applications the inserts are clamped in the body and are "indexable". That is, when one cutting edge is damaged the insert may be unclamped, removed from the cutter body, reoriented ("indexed"), and then reinstalled with one of its remaining sharp edges in position to resume machining. When all cutting edges have been used on a particular insert, it is thrown away and replaced with a new one. The fact that only the inserts must be replaced, and not the complete milling cutter, has obvious economic advantages.

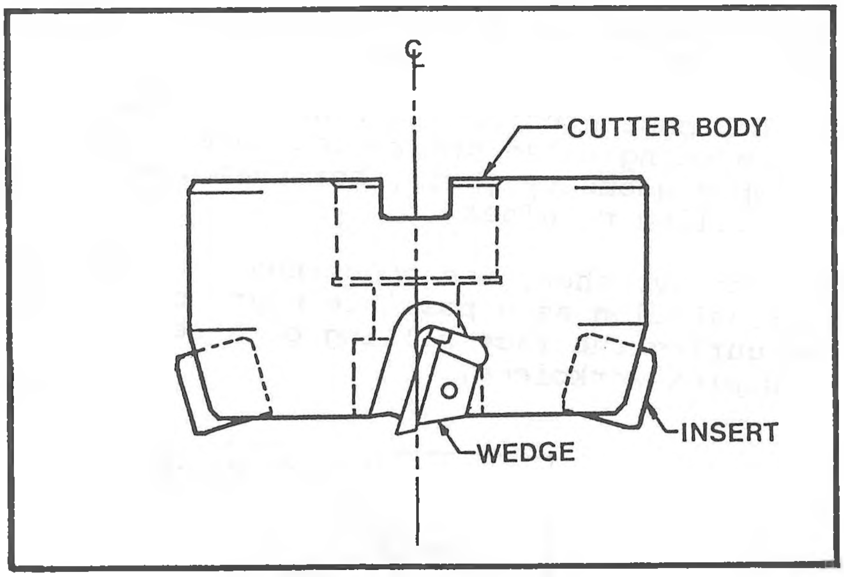

Figure 1. An indexable insert face milling cutter.

Experience has shown that during face milling of relatively compliant workpieces, such as an aluminum transmission housing, it is the workpiece itself, and not the machine structure or the milling cutter body, which is the primary radiator of noise.

Although it is theoretically possible to reduce the noise generated during the milling process by employing damping pads [1], enclosures [2], or other peripheral methods, the practical problems of additional cost, space limitations, maintenance difficulties, workpiece deflections, etc. make these solutions generally unattractive.

The reduction of workpiece vibration, and hence noise, at its source is, in every respect, the most desirable solution. This can best be achieved by modifying the milling cutter in such a manner as to minimize the workpiece response to the excitation imparted by the milling cutter insert engagements.

Studies by various researchers have indicated that the non-uniform spacing of events in a multi-event cycle has the potential to reduce vibration and noise generation. Varterasian [3] showed the efficacy of this general procedure when applied to snow tire noise reduction. Also, Ewald et.al. [4], Krishnappa [5] and Segawa [6] have shown that the same principle can be employed successfully in fan design. Doolan et. al. [7], [8] and Burney and Wu [9] have demonstrated such a technique for use with milling cutters. Applied to face milling cutters, this technique results in an irregular cutting insert pitch. Such an approach is highly attractive since it attacks the source of the noise generation without recourse to expensive and difficult-to-maintain control methodologies. There would be essentially no cost penalty associated with the production of a face mill with non-constant insert pitch relative to the familiar cutter with uniformlly spaced inserts.

Unfortunately, most studies describing the use of non-constant insert pitch in reducing noise generation have been concerned with workpieces of simple geometry (bars, box-beams, etc.) using small, single-purpose, milling machines.

The present study, then, was concerned with the application of insert spacing modulation as a possible means of reducing the noise levels produced during the face milling of a relatively compliant, geometrically complex workpiece.

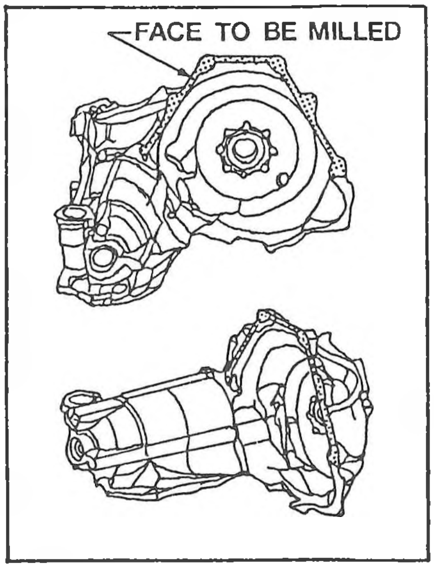

Figure 2. Two views of the transmission case.

METHODOLOGY

All tests were conducted during the machining of the engine ounting face of a cast aluminum, automobile transmission case. The ocation of this face on the transmission case is shown in Figure 2. he engine mounting face is geometrically "complex" as it results in ontinuous variation of the insert entrance and exit angles, and in he effective width of cut. The path followed by the face milling utter during each machining cycle is shown in Figure 3.

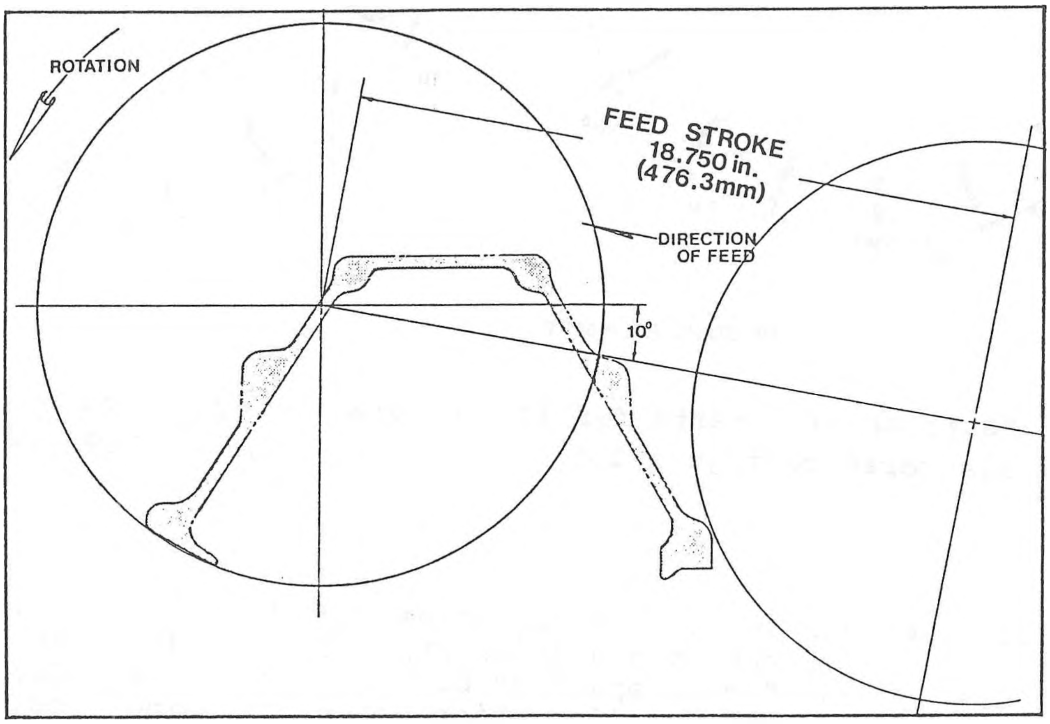

Figure 3. Relationship between the part profile and cutter path.

A total of five different cutter configurations, all with cutting eighteen indexable inserts, were employed in this study.

The tooling consisted of the following three cutter bodies:

i) A Valenite 406 mm diameter ring-type cutter with equally spaced insert pockets.

ii) A Valenite 406 mm diameter ring-type cutter with a 1° staggered pocket configuration. This cutter employed standard (unmodified) inserts. This configuration is designated "1° STAG" in this paper. See Figure 4.

iii) A Valenite 406 mm diameter ring-type cutter with a 1/2° staggered pocket configuration. The cutter employed standard inserts. This configuration is designated as "1/2° STAG" in this paper. See Figure 5.

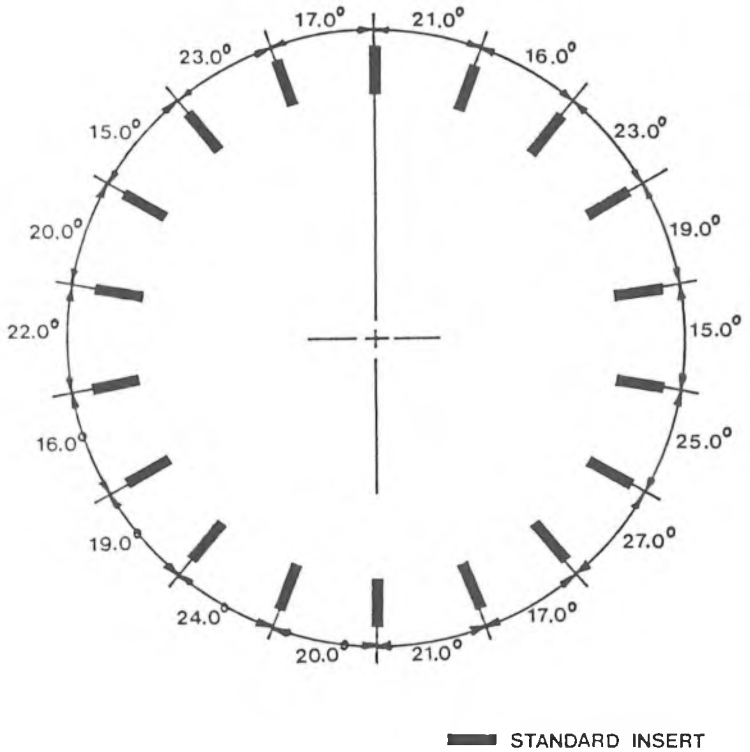

Figure 4. Position of inserts for 1° staggered configuration.

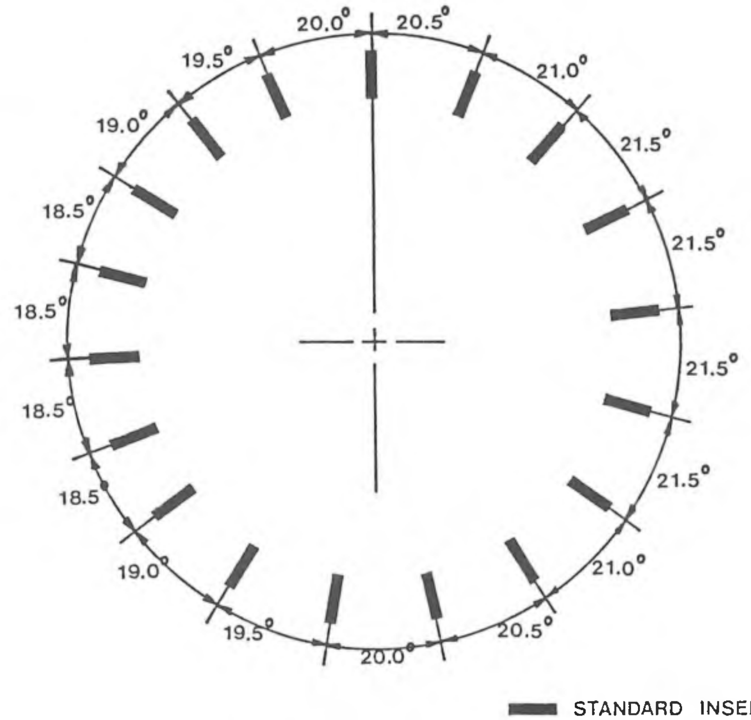

Figure 5. Position of inserts for 1/2° staggered configuration

Insert pockets in all cutter bodies provided a 10° positive axial and radial rake for the standard inserts. In two cases the standard inserts used in the "equal spacing" cutter body were modified to provide a total of three configurations from this single cutter body:

i) Standard inserts set into the equally spaced pockets. This configuration is designated as "EQ. SP.".

ii) Five standard inserts were modified by grinding them back 1.5 mm and installed at randomly chosen positions. The remainder of the pockets employed standard inserts. This configuration is referred to as "EQ. SP. 5 GR." in this paper. See Figure 6.

iii) Five standard inserts were modified by grinding with a 1.5 mm smaller inscribed circle (I.C.) and installed at the same positions as in (ii) above. The remainder of the pockets employed standard inserts. This configuration is designated "EQ. SP. 5 I.C.". See Figure 6.

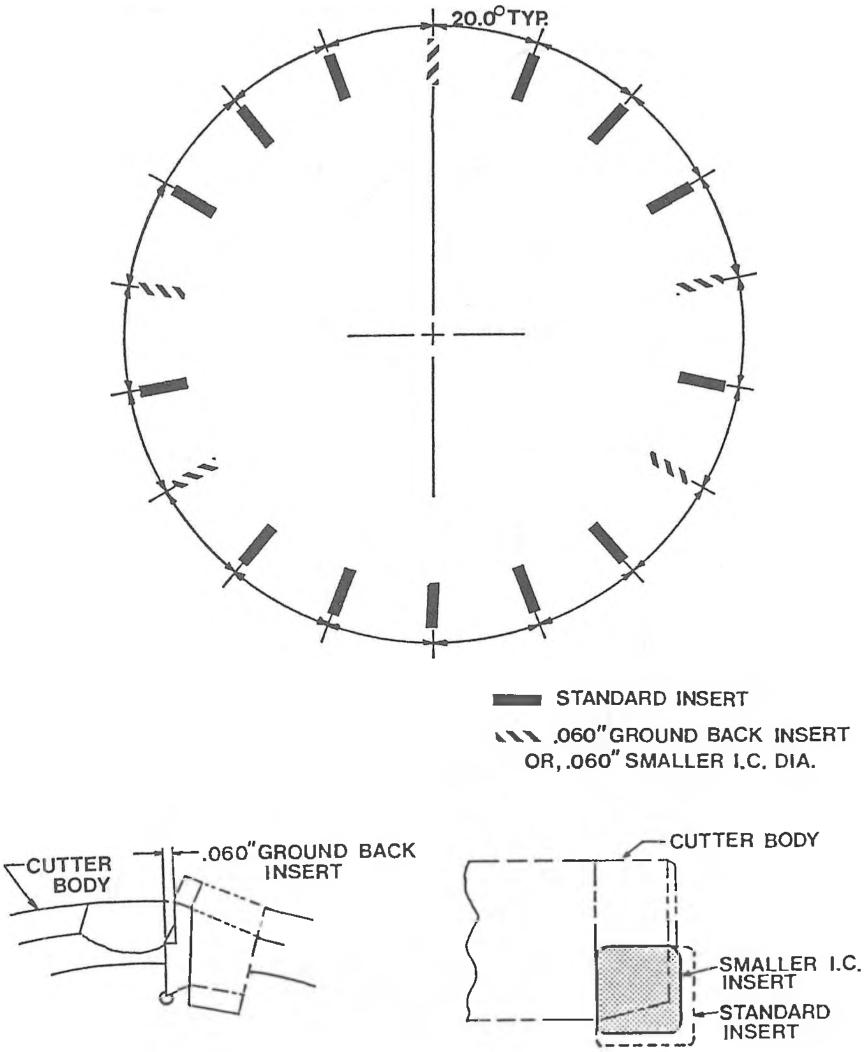

Figure 6. Position of inserts for equally spaced configuration with either five inserts ground back or five inserts with smaller inscribed circle.

The "1° STAG" and "1/2° STAG" configurations were chosen as representative of the design approach suggested by Vanherck [10] and Varterasian [11]. Basically, the insert spacing approximates a sinusoidal variation around the cutter. This can be seen quite clearly in Figure 7. In this figure the ratio of the actual pitch in degrees to the average pitch in degrees is plotted for each tooth. For the case of the "1/2° STAG" cutter the variation is reasonably smooth. For the "1° STAG" cutter the variation is much coarser with multiple crossings of the "EQ. SP." line. Obviously, on such plots a cutter with equally spaced inserts will be represented by a horizontal straight line, since each insert will have the same L/L_{avg} value. Note that the solid lines joining the points on these figures are used only to enhance the pattern formed by the plotted points and do not signify the existence of a continuous relationship between these points.

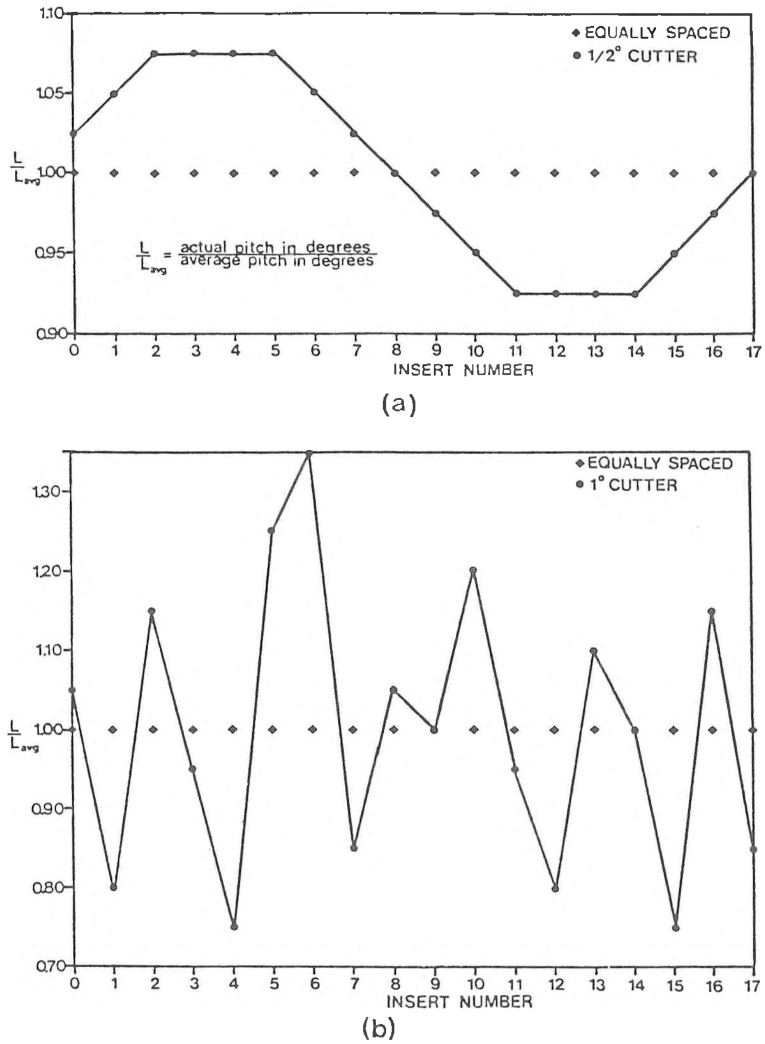

Figure 7. Plot of insert spacing for, (a) 1/2° STAG, or (b) 1° STAG.

The cutter configurations "EQ. SP. 5GR" and "EQ. SP. 5IC" were based on techniques employed by Reif [12] so successfully in a previous field application. In the present case it was hoped to determine whether small random perturbations of the cutting edges guarantee a reduction in noise relative to the evenly spaced configuration. It is generally agreed [13] that any change from even spacing improves the chatter resistance of a face milling cutter; however, it has not been shown that simple, random variations in insert pitch always result in noise reductions. These cutters were expected to help clarify the situation.

The "EQ. SP." configuration was employed as the "control" against which the results from the other cutters would be compared. This configuration is the industry standard, although there are some non-uniform pitch cutters presently in volume production, primarily to increase chatter resistance.

The cutter spindle rotated at 967 rpm for all tests. This translates into a surface speed of 21 m/s and a feed per tooth of approximately 0.2 mm for the equally spaced cutter. These are quite conservative values and would not be expected to put undue stress on the cutting inserts. They are, in fact, indicative of values which might be chosen for the production situation where reasonable tooth life would be desired.

During the test sequences, the sound levels generated throughout the entire 9.4 second cutting process were tape recorded for later analysis. Each noise measurement was obtained at the same position along an unobstructed line of sight to the workpiece. Samples of both the background and idle (spindle rotating but not cutting) noise levels were recorded for use in "correcting" the cutting noise levels. Measurements were made for each milling cutter configuration at seven depths of cut, from 2.1 mm to 3.6 mm. All noise measurements were made on the actual high-volume transfer machine during the "run-off" period and were A-weighted. Calibration signals were recorded both at the beginning and end of each test sequence.

RESULTS

To permit comparison of the effect of the various cutter configurations on cutting noise levels, the Leq value for each trial cut was calculated and the results summarized in Table 1. The blanks in the table indicate measurements which for various reasons (equipment failure, set-up difficulties, etc.) were not ultimately obtained although they were initially planned.

SPINDLE SPEED 967 rpm

CUTTER	DEPTH OF CUT - in. (mm)						
	0.083 (2.1)	0.093 (2.4)	0.103 (2.6)	0.113 (2.9)	0.123 (3.1)	0.133 (3.4)	0.143 (3.6)
EQ. SP.	88	88	88	89	90	91	92
EQ. SP. 5GF	88	89	89	90	90	93	93
1° STAG.	90	91	92	92	92	94	94
1/2° STAG.	-	92	-	91	92	92	93
EQ.SP. 5IC.	92	92	92	93	93	93	-

Table 1. Summary of the L_{eq} values obtained during the test sequences.

A review of the data contained in Table 1 indicates that the four milling cutters employing non-uniform insert spacing generated noise levels similar to, or higher than those of the equally spaced control. For all five cutter designs the noise level increased with depth of cut, although both the "1/2° STAG" and "EQ. SP. 5 I.C." configurations seem to indicate less sensitivity to this variable over the range studied. See Figure 8.

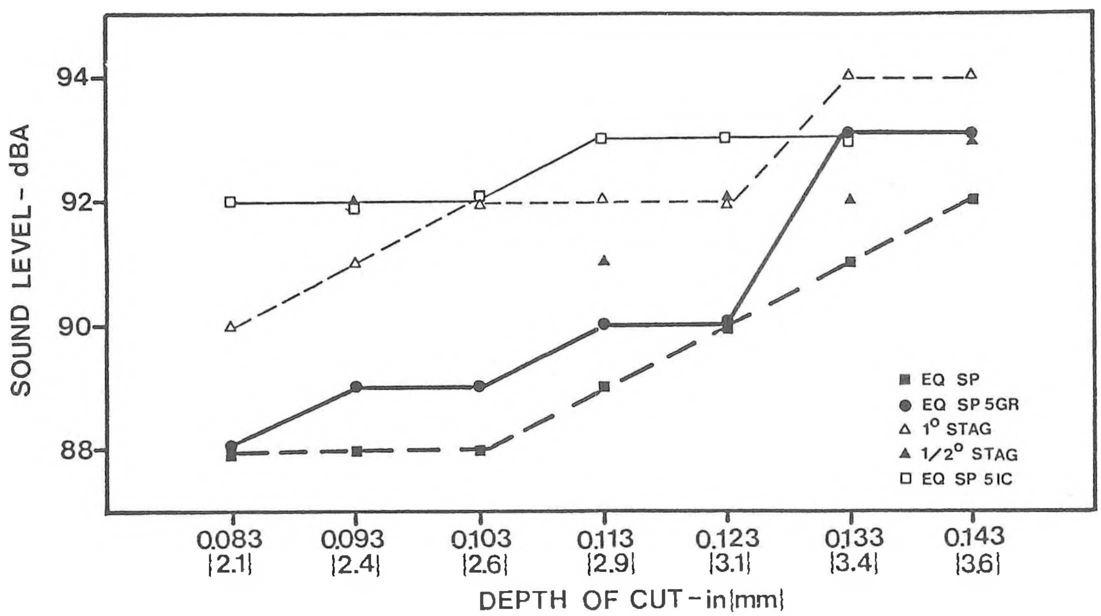

Figure 8. Energy equivalent sound level versus depth of cut.

Frequency spectra of the noise generated by each cutter design indicate that the non-uniform insert pitch caused redistribution of the sound energy over a wider bandwidth when compared with the equally spaced cutter. This phenomenon is illustrated in Figure 9. In this instance, Test #24 and Test #25 produced the same Leq value, yet the redistribution of energy due to the non-uniform pitch employed in Test #24 is readily apparent. The cursor shown marks the "EQ. SP." cutter's fundamental "insert engagement frequency" (frequency of cutter rotation x number of inserts) while the open circles mark the positions of the first fifteen higher harmonics of this fundamental frequency.

All frequency spectra in this paper are shown with the magnitudes of the components presented in the form of the dimensionless ratio p/p_r, where p is the r.m.s. sound pressure and p_r is the standardized reference pressure of 0.00002 Pascals.

It should be noted from Figure 9 that although no change in overall Leq value was achieved, Test #24 indicates a reduction in "noisiness" relative to Test #25 due to the significant decrease in sound energy concentrated at discrete and harmonically related components [14]. This result was not restricted to particular test groupings but was found to be generally applicable.

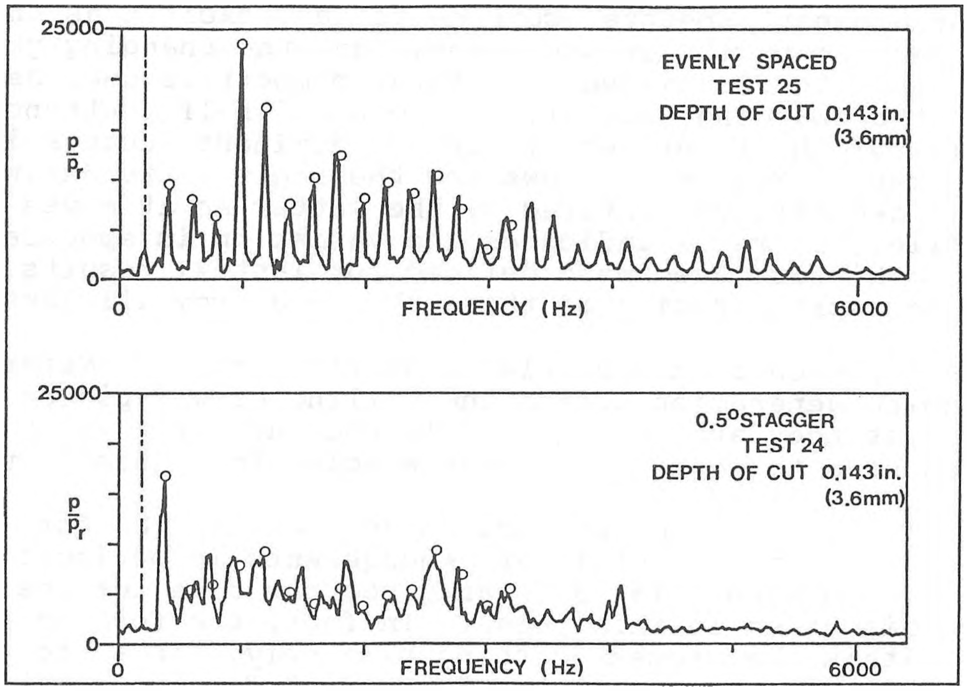

Figure 9. Comparison of spectra from two test cuts.

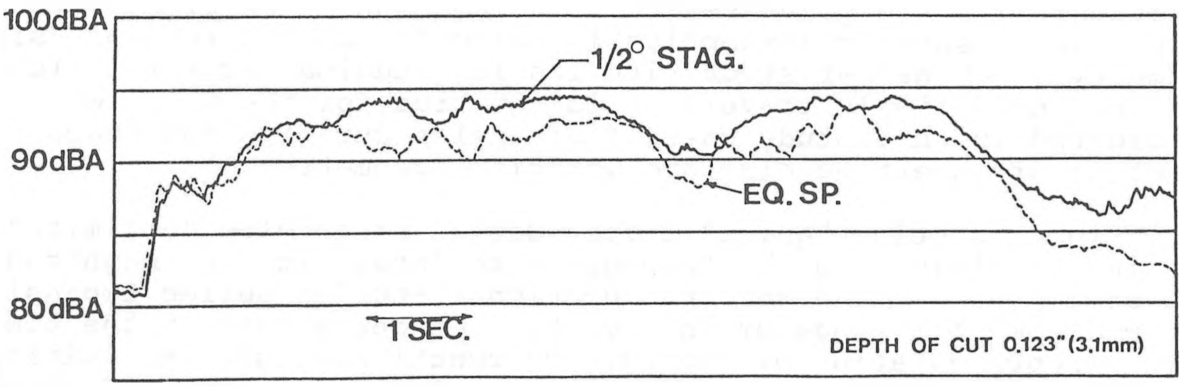

Figure 10. Comparison of sound levels generated by two different cutters.

A review of all the sound level-versus-time readings which were generated during the cutting tests of each milling tool indicates that, although unique, they do exhibit remarkable similarities. Figure 10 shows a comparison of the noise levels produced during Test #5 ("EQ. SP." cutter; depth of cut 3.1 mm) and Test #36 ("1/2 STAG" cutter; depth of cut 3.1 mm). These are significantly different cutter geometries and yet it is apparent that various common regimes of noise generation (characterized by changes in overall sound level and the predominant spectral components) are excited as the cutter moves across the part. It would seem that the changing geometry of the part (and its associated structural properties such as stiffness, etc.) and the changing geometry of the cut itself (entrance angle, exit angle, width of cut, etc.) are the dominant factors in producing these regimes. Figure 11 shows how the regimes are defined by the changes in geometry encountered by the cutter as it moves over the part profile. Figure 12 indicates the variation in spectral content for three arbitrary "regimes" defined for Test #1 results. Such results are representative of those obtained from all test sequences.

Certainly such phenomena play a critical role in determining the overall noise generation during the milling of workpieces of complex geometry, yet they are not adequately accounted for in the existing procedures used to determine insert spacing for "quiet" cutters.

Generally such design procedures assume that the forcing function associated with the cutter insert engagements is periodic within the cutter rotation when this is clearly not the case for the type of workpiece discussed in this paper. In fact, the forcing function is periodic within the process cutting time only. Thus, for our case of an 18 insert milling cutter, the "periodic" forcing function does not consist of 18 unique force pulses as existing design procedures would assume, but a total of 2,727 force pulses (total process cutting time in seconds x spindle r.p.s. x number of cutter inserts).

It is also normally assumed that the modulation of the force pulse durations within a given period is a function of cutting tooth spacing only. While such an assumption is valid for a workpiece of "simple" geometry (such as bar stock with its longitudinal axis set along the axis of the cutter's travel) it is not true for the workpiece considered in this study where force pulse duration and shape are a function of insert spacing and workpiece geometry.

Since existing "quiet" cutter design strategies "optimize" insert spacing by minimizing the "energy" associated with the magnitude of the components of the forcing function's Fourier Series Expansion (over a specific range of interest), then any errors in the time domain representation of the forcing function result in minimization of "energy" associated with the "wrong" Fourier Series. Consequently, this produces a cutter design which is not "optimal" (minimum noise generation) for the actual operating conditions.

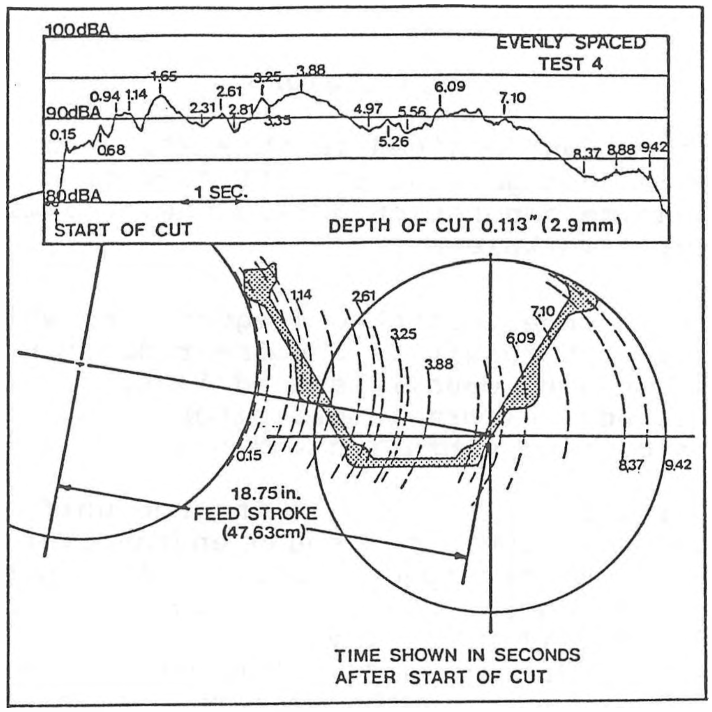

Figure 11. Sound level generation as a function of cutter position.

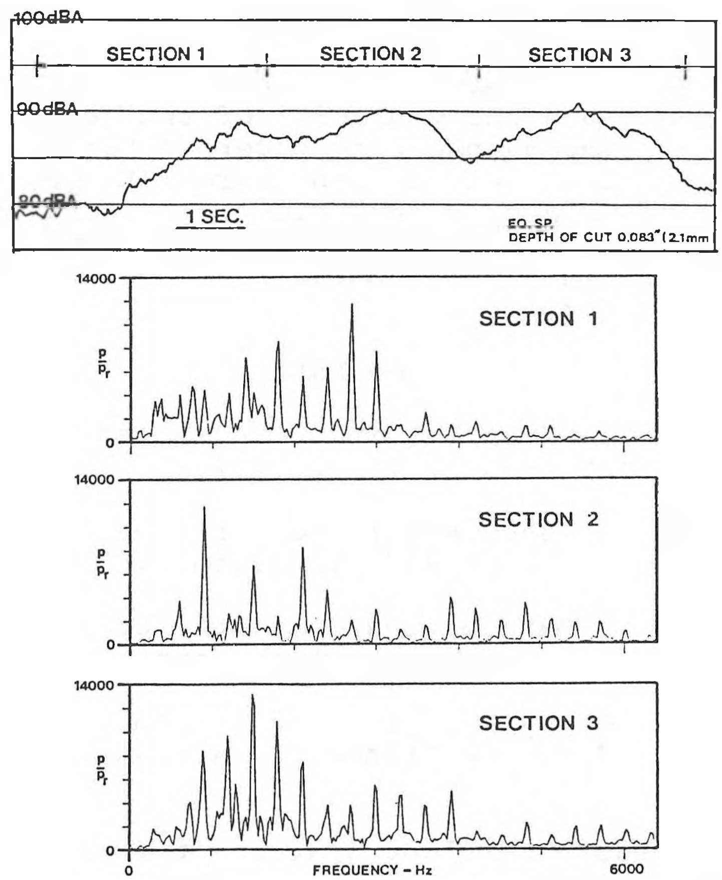

Figure 12. Comparison of the spectral content of three arbitrarily defined regimes.

CONCLUSIONS

From the information obtained in this study the following conclusions can be made regarding the efficacy of non-uniform insert pitch in reducing noise generation during the face milling of a geometrically complex workpiece.

i) The non-uniform insert pitch configurations which were used in this study did not result in a noise reduction relative to a standard cutter with equally spaced inserts. Thus it is apparent that non-uniform insert pitch does not guarantee a reduction in cutting vibration and noise.

ii) Spectral analysis indicated that the non-uniform insert pitch did in fact redistribute the sound energy over a wider bandwidth compared to the evenly spaced cutter. Although this rearrangement of energy was not sufficient to provide a reduction in overall noise level, it did provide a significant reduction in the "noisiness" of the cut. This was the result of a significant decrease in the magnitude of discrete, harmonically related components.

iii) The complex nature of the part geometry produced, during each cut, several well defined noise emission regimes, within each of which the overall level and noise spectrum are unique.

iv) It was evident that the predominant source of noise during the cutting process was the vibration of the workpiece. Its complexity and dependence upon numerous variables makes modifications to the excitation source (the milling cutter) the only practical method of reduction. It is equally evident that existing procedures for determining the unequal distribution of inserts to produce "quiet" cutters are not suited to workpieces of complex geometry.

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