# GFRP의 2차원 절삭에서 주파수 스펙트럼과 절삭메카니즘과의 상호연관성에 관한 연구

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# Frequency Spectrum and Its Correlation with Cutting Mechanisms in Orthogonal Cutting of Glass Fiber Reinforced Plastics

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**Abstract :** This study discusses frequency analysis based on the frequency spectrum and process characterization in orthogonal cutting of fiber-matrix composite materials. A sparsely distributed idealized composite material, namely a glass reinforced polyester(GFRP) was used as workpiece. The present method employs a force sensor and the signals from the sensor are processed using the fast Fourier transform(FFT) technique. The experimental correlations between the different chip formation mechanisms and power spectrum are established. Effects of fiber orientation, cutting parameters and tool geometry on the cutting mechanisms are also discussed.

**초 록 :** 본 연구에서는 복합소재인 GFRP(Glass Fiber Reinforced Polyester)의 2차원 절삭공정에서 주파수 스펙트럼과 절삭 메커니즘과의 연관성에 관하여 논의한다. 해석방법으로는, 공정중 발생하는 절삭력 신호를 FFT에 의해 주파수 분석하고 주파수 스펙트럼과 다양한 칩형성 메커니즘과의 연관관계를 모델링한다. 특히, 섬유경사각(Fiber orientation angle), 절삭변수 그리고 공구형상이 절삭 메커니즘에 미치는 영향을 평가하였다

**Key Words :** GFRP, orthogonal cutting, frequency spectrum, chip formation

## Nomenclature

$\theta$ : Fiber orientation angle
$\theta_e$ : Effeective fiber orientation angle
$\alpha$ : Tool rake angle
$\gamma$ : Tool clearance angle
$P(\omega)$ : Power spectrum
$\omega$ : Frequency
$\omega_r$ : Frequency with 90 fiber orientation angle
$x(n)$ : Force signal
$\Delta T$ : Time interval (sampling interval)
$t_1$ : Depth of cut
$f$ : Feed rate
$V_w$ : Cutting speed
FOA : Fiber orientation angle
EFOA : Effective fiber orientation angle

## 1. Introduction

In recent years, composite materials such as fiber reinforced plastics(FRP) have gained considerable attention in the aircraft and automobile industries due to their light weight, high modulus and specific strength. A typical FRP component is molded to near net-shape and subsequently machined to meet the geometric tolerance and surface finish requirement. The reliability of machined components, especially for FRP in high strength applications, is often critically dependent upon

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the quality of surface produced by machining since the surface layer may drastically affect the strength and chemical resistance of the material. In practice, control of chip formation appears to be the most serious problem since the chip formation mechanism in composite machining has significant effects on the finished surface.1~5)

Despite the in-plant calibration needed, process modeling and characterization based on a empirical model are frequently performed to realize the practical implementation of an intelligent sensor. Among various sensor signals available nowadays, force (vibration) signals from various types of machining operations were found to contain very rich information about the process6). The fundamental understanding of the cutting force signals and frequency analysis therefore play an important role in the monitoring and control of machining processes.

In the past, the research efforts have been directed mainly toward understanding the physics of machining composites. For practical applications, multi-directional materials are of much greater importance. The use of materials with unidirectional laminate, however, provides the fundamental understanding of the relationships between fiber-matrix cutting mechanisms and process variables. The present study involves frequency analysis based on the frequency spectrum and process characterization in orthogonal cutting of a fiber-matrix composite materials. A sparsely distributed idealized model composite material, namely a glass reinforced polyester (GFRP) was used as a workpiece. The present method employs a force sensor and the signals from the sensor are processed using a fast Fourier transform (FFT) technique. The experimental correlation between the different chip formation mechanisms and model coefficients are established. The effects of fiber orientation, cutting parameters and tool geometry on the cutting mechanisms and surface quality are also discussed.

## 2. Orthogonal Cutting of GFRP

Machining of GFRP involves shearing and cracking of matrix material (polyester), brittle fracture across the fiber (glass), fiber pull-out and fiber-matrix debonding (by tensile fracture), and delamination prior to final fracture both in the chip and below the cutting plane depending on the fiber orientation. The previous investigation performed by the authors indicated that experimentally measured forces and machining stresses in the orthogonal cutting of GFRP were dependent heavily on the reinforcement and its orientation3,7). Accordingly, the chip formation mechanism changes with fiber orientation. Damage of the machined surface was found to be highest when machining was performed with roving oriented 45° towards the cutting edge or the fiber orientation angle(FOA) $\theta$=135° in Fig. 1. Three distinct mechanisms, i.e., cutting, shearing and fracture along the fiber-matrix interface were then identified. More specifically, depending on the fiber orientation, cutting mechanisms can be categorized into the following 4 types:

(1) Type I(0° fiber orientation): the cutting mechanism is characterized by Mode I loading and fracture along the fiber-matrix interface, Mode II loading through tool advancement, and the fracture perpendicular to the fiber direction under bending load. Combined effect of these mechanisms can be manifested by the delamination of adjacent fiber layers along the machined surface (or fiber-matrix debonding).

(2) Type II(15°-75° fiber orientation): In this positive fiber orientation, the cutting mechanism is composed of fracture from compression induced shear

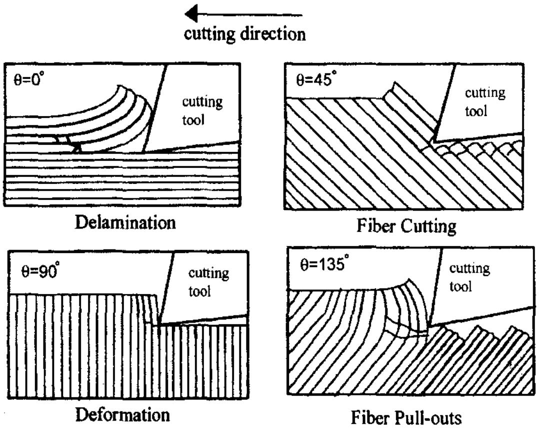


Fig. 1. Schematic of cutting mechanisms in orthogonal cutting of GFRP

across the fiber axis and interfacial shearing along the fiber direction which eventually causes fiber-matrix debonding.

(3) Type III(75°-90° fiber orientation): the cutting mechanism is characterized by compression induced fracture perpendicular to the fibers and interlaminar shear fracture along the fiber/matrix interface.

(4) Type IV(beyond 90° fiber orientation): the cutting mechanism in this type is basically similar to Type III. However, intermittent fracture across the fiber axis is visible, which in turn contributes to the burst type force signal.

## 3. Frequency Analysis

Since the interpretation of raw force signals other than energy contents is very difficult due to their random nature, they need to be processed to provide useful information on the cutting mechanisms and other process characteristics. In this study, two signal processing methods that use discrete sampled data to develop the stochastic model are tested, and their performance are compared. First, power spectral analysis of the force signals was performed. It is widely accepted that certain frequency components of the power spectral density of force signals are sensitive to cutting mechanisms in machining.[6] These frequency components can then be used as features for characterizing cutting mechanism. The power spectral density of the discrete signal *x(n)* in the time domain yields the signal power contained at different discrete frequencies and can be obtained from

$$P(\omega) = \sum_{k=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} x(n)x(n+k)e^{-jk\omega} \qquad (1)$$

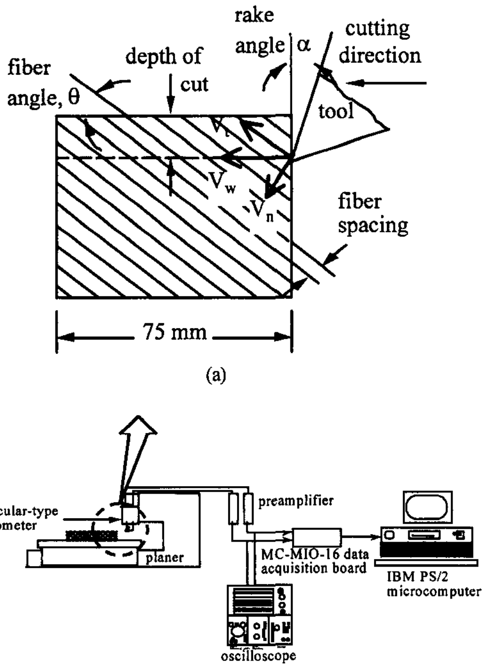
where $\omega$ is the discrete frequency and $S(\omega)$ is the signal power at this frequency. For efficient mapping of input patterns in the time domain into the frequency domain, the FFT technique was used. The resulting spectrum were smoothed by taking band averages to attain statistical stability and these averages were used for further analysis.

## 4. Experiment

A series of orthogonal cutting experiments were conducted for both CuFRP and GFRP composite materials. The GFRP plate were 4.0mm thick with glass yarns of 0.4mm diameter arranged approximately 0.8mm apart. The reinforcement was arranged in the middle of the plate. Constituents of GFRP are given in Table 1. The workpieces were mounted on a Rockfort Shaper-Planer equipped with modified hydraulic system to provide a steady cutting motion. About 25mm of the ma-

**Table 1.** Constituents of GFRP used in this study

| | GFRP |
|---|---|
| Resin | Unsaturated polyester polymal 6304, 6320F at a ratio of 1:1 |
| Reinforcement | ECG-75-11/2 3.3 S NA glass yarn of 0.4mm diameter |
| Reinforcement Volume Fraction (%) | 0.85% |
| Post Curing | 120C for 2 hours |



(a)

(b)

**Fig. 2.** Designation of angles and schematic diagram of experimental setup

terial was exposed for machining each time. Multipurpose C2 grade carbide inserts were used in dry cutting of GFRP. Schematic diagram of data acquisition and experimental setup is given in Fig. 2. Schematic of the workpieces and relative angles between the cutting direction and fiber orientation is also shown in Fig. 2.

The force signals were obtained using a three-dimensional circular-type strain gage dynamometer that was attached to the tool post. Signals were passed through a pre-amplifier and sampled using a National Instrument MC-MIO-16 data acquisition board. Sampling rate was 5000Hz. The sampled signals were stored in a IBM PS/2 computer for further analysis. Frequency spectrum were obtained using MATLab software. The machined surfaces were examined by projecting back light on to the side of the machined workpiece to observe and quantify the machining damage. Detailed description of the experimental procedures is given elsewhere$^{1\sim3)}$.

## 5. Results and Discussion

### 5.1. Effect of Fiber Orientation

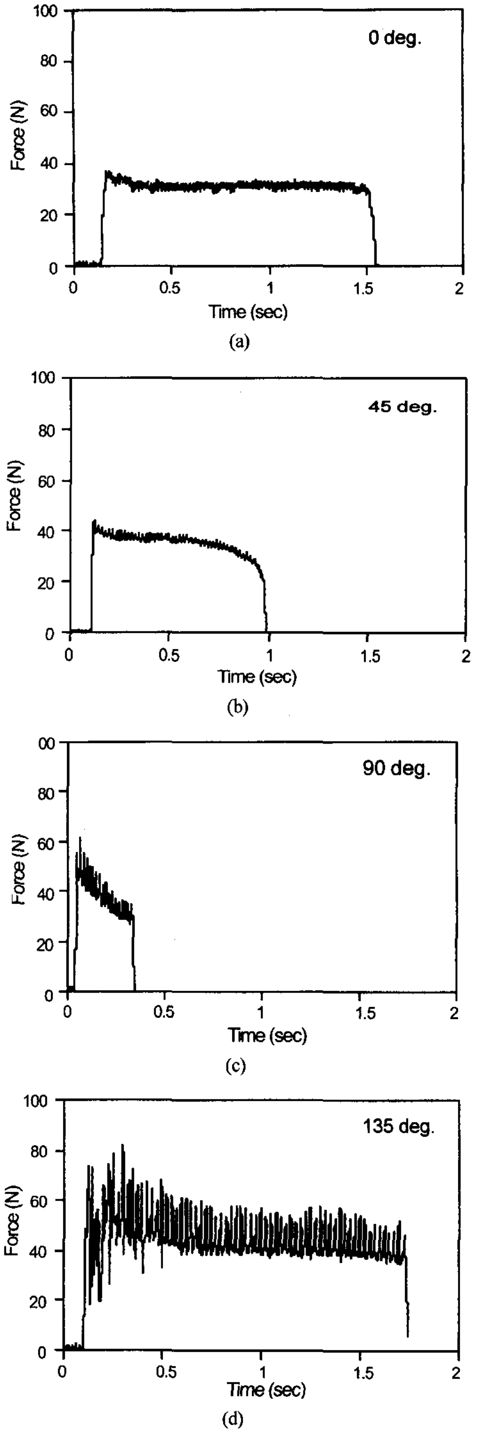
Fig. 3(a) through 3(d) show the typical cutting force signals when the fiber orientation angle is 0°, 45°, 90° and 135°, respectively. The reference values of cutting parameters are cutting speed of 3m/sec, tool rake angle of 20° and depth of cut of 0.051mm. Positive tool rake angle was selected as the reference value since negative or zero rake angle are seldom used in practice. It is apparent that even the unprocessed force signals exhibit peaks due to fiber cutting. In general, the power spectra of force signals in composite machining are dominated by the frequency component that corresponds to the frequency of mechanical shock coming from the abrupt engagements of tool in fiber cutting. The cutting force signal is, therefore, periodic in nature with a fundamental frequency determined by the number of fibers in unit length, the fiber orientation angle and the cutting speed. The fundamental frequen- cies for different combinations of cutting speed and fiber orientation angle are summarized in Table 2. This fundamental frequency is doubled if the cutting speed is doubled from 3m/min to 6m/min. Note that all the spectral power components obtained were normalized with respect to the total power of the spectrum so that all the spectra have unit total energy. This makes the spectral components invariant to the absolute energy and enhances the comparative variation of characteristic features for different cutting mechanisms. The energy at 0 Hz(DC component), which represents the average level of force, does not show enough sensitivity to the cutting mechanisms rendered by different fiber orientation angles$^{1\sim3)}$. It is, therefore, not considered for frequency analysis in this study.

**Table 2.** Fundamental frequencies for different combinations of cutting speed and fiber orientation angles

| Fiber Orientation Angle | Fundamental Frequency | |
|---|---|---|
| | 3m/min | 6m/min |
| 30° | 31.24Hz | 62.48Hz |
| 45° (135°) | 44.12Hz | 88.24Hz |
| 90° | 62.50Hz | 123.00Hz |

The peak of average cutting force at 90° fiber orientation clearly indicates onset of different cutting mechanism$^{8)}$. In case of 0° fiber orientation, no fiber cutting is expected and fundamental frequency is 0 Hz(DC component). The small downward spikes in Fig. 3(a) indicate the occasional delamination of fiber from the matrix. Its frequency depends on the material properties of matrix and fibers, tool geometry and cutting parameters. Between peaks, the signals are basically due to cutting matrix material which is isotropic in nature. Energy in other frequency region in this case does not provide any discriminating information on the fiber orientation and related cutting mechanisms. Therefore, the cutting mechanism of TYPE I needs no further attention and is not considered in this study.

Fig. 4 shows the normalized power spectrum for 90° fiber orientation angle. Glass fibers in 90° orientation are most densely spaced so that the fundamental frequency in this case has the highest value. The fundamental frequency was identified with an arrow in the figure and agreed very well with the listed value in Table 2. Fig. 5 shows the effect of fiber orientation on the normalized frequency spectra where the fundamental frequencies for 45° and 135° fiber orientations



(a)

(b)

(c)

(d)

Fig. 3. Cutting force signal obtained for different fiber orientations in cutting GFRP. Reference cutting parameters are: cutting speed, 3m/min; tool rake angle, 20°; depth of cut, 0.051mm

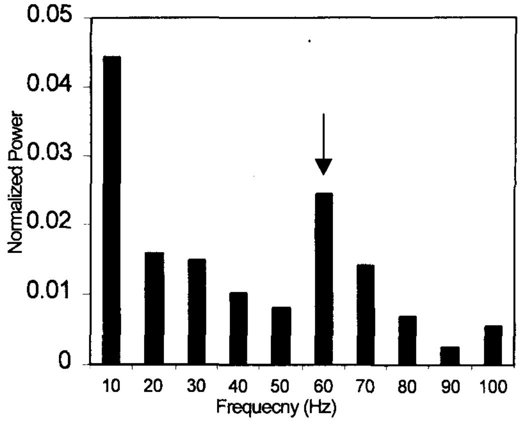


Fig. 4. Normalized power spectrum for 90° fiber orientation angle. Reference cutting parameters are same as in Fig. 3

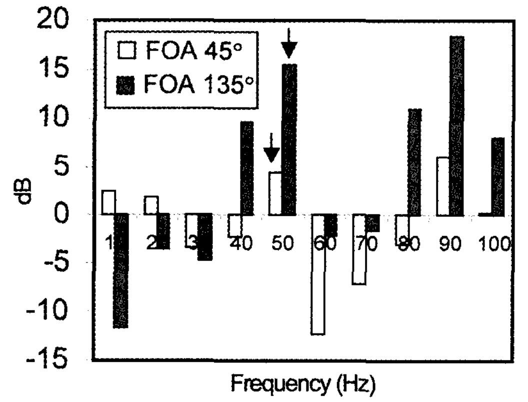


Fig. 5. Effect of fiber orientation on the normalized frequency spectrum in cutting GFRP. Reference cutting parameters are same as in Fig. 3. The reference fiber orientation angle is 90°

are also marked with the arrows. The reference fiber orientation angle is 90°. In the figure, the relative variation of normalized power with the fiber orientation angle is represented by signal to noise ratio(ratio of the power at frequency $\omega$ to the power at frequency $\omega_r$ with 90° reference fiber orientation) in dB scale as

$$SNR = 20\log\left(\frac{\omega}{\omega_r}\right)\ (dB) \qquad (2)$$

The cutting stresses for fiber orientation angle greater than 0° tends to increase only when the tool is in the vicinity of fiber regardless of the fiber orientation[3,7]. The lower frequency components of the force signal are, in general, dominated by the components originating from the discontinuous nature of the fiber cutting and do not exhibit high sensitivity to chip formation mechanisms. It is also interesting to note that there is appreciable amount of energy above the fundamental frequency with 135° fiber orientation. This may be attributed to the intermittent inter-laminar fracture that causes burst type cutting force signal. Severe fiber pull-out also contribute to the high frequency contents of the force signal.

### 5.2. Effect of Tool Geometry

Tool geometry was found to have significant effect on the frequency characteristics of measured force signal. Fig. 6 shows the effect of tool rake angle on the frequency characteristics of force signal. As the tool rake angle decreases from positive to negative value, less energy contents in the region below the fundamental frequency is clearly seen. The acute cutting edge (higher tool rake angle) induces Mode I loading and reduces the degree of Mode II component, provided that tool clearance angle is positive.[8] This will certainly contribute to the low frequency contents of the measured force signal by intermittent delamination.

To further explain such energy shift, the effective fiber orientation angle(EFOA, (e) can be conveniently defined as the relative angle between the tool rake face and the fiber orientation, i.e., $\theta_e = 90° + (\theta - \alpha)$ in Fig. 2[9]. For example, cutting 90° oriented GFRP with 20° rake tool is geometrically equivalent to cutting 70° oriented GFRP with 0° rake tool. Tool clearance face is assumed not to interfere with the workpiece in defining $\theta_e$. It was observed in graphite/epoxy composite cutting experiments that tool clearance angle has limited effect on the average cutting force level[8]. Fig. 7(a) and (b) shows the normalized frequency spectrum for different effective fiber orientation angle. It is evident from the figure that the signals for a given effective fiber orientation angle exhibit similar frequency characteristics.

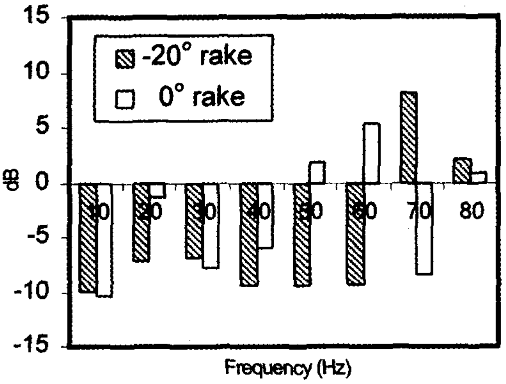
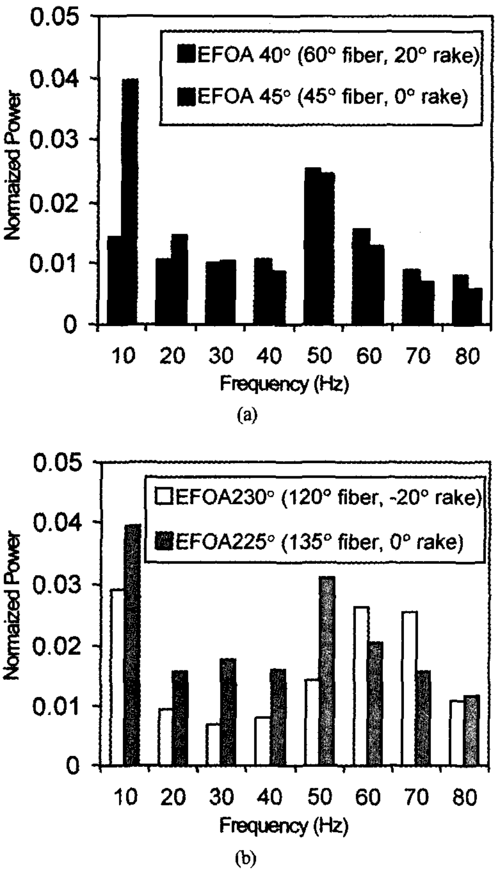


Fig. 6. Effect of tool rake angle on the normalized frequency spectrum. Reference cutting parameters are same as in Fig. 3. Reference fiber orientation angle and tool rake angle are 90° and 20°, respectively

The tangential and normal components of cutting velocity to the fiber orientation, i.e., $V_t(=V_w \cos\theta)$ and $V_n(=V_w \sin\theta)$ in Fig. 2, are determined solely by the fiber orientation angle $\theta$. The tangential component of



(a)

(b)

Fig. 7. Normalized frequency spectrum for different effective fiber orientation angle; EFOA 40° and 45°, (a); EFOA 225° and 230°, (b). Reference cutting parameters are same as in Fig. 3 except the tool rake angle

cutting velocity works to induce fiber-matrix debonding and inter-laminar fracture, which in turn generate signals with frequency components above the fundamental frequency. The normal component is responsible for compression induced fracture across the fiber. Furthermore, fiber orientation angle other than 90° always induces lower fundamental frequency. As for the tool rake angle, as more Mode I fracture occurs along the fibers for the case of high tool rake angle(acute cutting edge), more low frequency signal with downward spikes originating from such phenomenon becomes evident. However, as the tool rake angle decreases, the interfacial shearing and compression induced fracture across the fiber is visible, which contribute to the high frequency contents of the force signal. Increasing tooi rake angle always brings about an increase in fiber orientation angle for a constant value of effective fiber orientation angle (or a relative angle $\theta$- $\alpha$). When normalized by the total energy, the effects of tool rake angle and fiber orientation angle appear to be mutually contradictory. Uniform energy distribution for a given effective fiber orientation angle in Fig. 7 is understandable in those respects.

## 6. Summary and Conclusions

Frequency analysis based on the power spectrum of measured force signal in orthogonal cutting of GFRP has been discussed. The force signal was found to exhibit different signal characteristics for different cutting mechanisms. Specifically, frequency characteristics in Type II cutting exhibit energy contents below the fundamental frequency region. This low frequency energy band is due to Mode I and Mode II loading which causes occasional delamination(fiber-matrix debonding) of fibers. Type III and Type IV cutting mechanisms are associated with more energy in the high frequency region originating from micro buckling, fracture along and across the fibers, and fiber pull-out. The effective fiber orientation angle, which is the relative angle between the tool rake face and the fiber orientation, was then introduced. With the effective fiber orientation angle being consistent with the power spectrum of force signal, one can conclude that the effective fiber orientation angle is consistent with the cutting mechanism involved.

**Table 3.** Experimental conditions for machining GFRP. Depth of cut is 0.051mm

| Class | Fiber Orientation Angle (FOA) (degrees) | Cutting Mechanism (Type) | Type of Chip | Cutting Parameters | | |
|---|---|---|---|---|---|---|
| | | | | Cutting Speed (m/min) | Rake Angle (degrees) | $\theta_e$ (Degrees) |
| 1 | 45 | II | C | 3 | 20 | 115 |
| 2 | 45 | II | D | 6 | 20 | 115 |
| 3 | 90 | III | C | 3 | 20 | 160 |
| 4 | 90 | III | D | 6 | 20 | 160 |
| 5 | 135 | IV | C | 3 | 20 | 205 |
| 6 | 135 | IV | D | 6 | 20 | 205 |
| 7 | 45 | II | - | 3, 6 | 0 | 135 |
| 8 | 45 | III | - | 3, 6 | -20 | 155 |
| 9 | 90 | IV | - | 3, 6 | 0 | 180 |
| 10 | 90 | IV | - | 3, 6 | -20 | 200 |
| 11 | 135 | IV | - | 3, 6 | 0 | 225 |
| 12 | 135 | IV | - | 3, 6 | -20 | 245 |
| 13 | 45 | - | - | 3, 6 | 0 | 135 |
| 14 | 60 | - | - | 3, 6 | 20 | 130 |
| 15 | 120 | - | - | 3, 6 | -20 | 230 |
| 16 | 135 | - | - | 3, 6 | 0 | 225 |

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