Identification of the Moving Noise Source in a Circular Sawblade by the Experimental Acoustic Intensity Technique

음향인텐시티법에 의한 원형 톱날에서의 이동소음원 규명

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ABSTRACT

This study investigates the feasibility of identifying aero-acoustic source occurring with rotating sawblade. The acoustic intensity technique takes useful advantage of 3-D, intensity vector flow and contour plots. The estimations of the near field behavior and the frequency domain vector or scalar acoustic intensity are measurement used for source identification purposes. According to the results, the turbulence produces in the vicinity of teeth of circular sawblade. The evidence of the influence of the vortex structure on the fluctuating sawblade pressure measurement is derived from the measured acoustic intensity. As the rotating speed increases, the interaction can be a significant source mechanism producing Doppler phenomenon.

요 약

본 연구에서는 회전톱날에서 발생하는 공기소음원(aero-acousticsource)규명의 실현가능성을 검토하였다. 음향인텐시티법은 3차원 선도(3-D plot), 인텐시티 벡터에너지선도(intensity vector energy flow), 등고선도(contour plot)등의 표현에 유용한 장점을 갖고 있다. 근거리 음장(near field)거동에 대한 추정, 주파수영역에서의 벡터 또는 스칼라 음향인텐시티는 소음원규명의 목적으로 사용되는 측정기법이다. 결과에 따르면 난류(turbulence)는 원형톱날의 이(teech) 부근에서 나타나며, 톱날의 변동압력 측정에서 와류구조의 영향에 대한 근거는 측정된 음향인텐시티에 의해 도출된다. 또한 회전속도가 증가함에 따라, 상호작용(interaction)은 도플러현상(Doppler phenomenon)을 일으키는 중요한 소음메카니즘이 될 수 있다.

I. Introduction

The circular sawblade is probably the most common cutting tool in the wood industry. The

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noise radiated by the idealing saw is excessive, and it results from a complicated mechanism. In order to seek methods of noise reduction, it is necessary to identify and rank the prominent sources of nise. If the noise sources are better understood, then the design process for reduced noise can be more useful. Traditionally, the noise source identification and rank ordering has been carried out by using the lead wrapping technique[1], near field holography[2], an inverse computational method[3], multi-dimensional spectral analysis techniques[4], and intensity measurement methods [5]. Methods attemps to reduce machinery noise ideally based on knowledge of the contribution of each individual noise to the overall radiated noise. Thus noise source identification is of vital importance for any noise reduction program, and a variety of methods have been developed in the past to serve this purpose. However, there is still a need for techniques that allow one to measure the distribution of noise sources with the operating in situ.

Preliminary work on the idling circular saw noise identification problem by Mote and Zhu in 1980 [6] and recently by Kimura[7] and Singh[8] at the University of California, Berkeley focused on the development of a phenomenological, kinematic source model and measurements of acoustic intensity in the normal, radial and tangential directions. They assumed that source models produce a specific acoustic intensity(time-averaged energy flux) in front of the saw. The acoustic intensity method has merit for noise source identification in a multi-source steady situation. The noise characteristics of individual source can be more accurately determined by near field acoustic intensity measurements. Recently there have been rapid developments in the techniques of measuring acoustic intensity. Of these techniques, the two closely-spaced microphone method has proven to be the popular.

In this study, the noise sources in the radial, tangential and normal directions to the circular sawblade are discussed. The purpose of this study is to identify the prominent noise producing directions in circular sawblade. The noise sources studied was a circular saw that served as an idealized model for a kinematic and dynamic dipole source.

II. Theory

2.1 Theory of Rotating Disk Acoustics Model

2.1.1 Review and Assumption

This study is primarily concerned with the feasibility of identifying aero-acoustic source(s) associated with the rotating disk including idling sound at a discrete frequency f_s will be considered as a schematic representation of the model as shown in Fig.1. A dipole force vector F will be assumed to be located in the vicinity of the disk edga. The emphases of the analysis are on the an alytical estimation of typical near field behavior and on the frequency domain vector or scaler techniques used to acquire near field data for diagnostic purposes.

A source S of frequency f_s is considered to be moving with subsonic velocity $M_s = V_s / C_0$ relative to the stationary observation point P located in the near field. First, the kinematics of the problem for both translating and rotating sources is examined : the rotating source is assumed to be in a steady angular rotation with f_d Hz. The observed frequency f_p is related to f_s and kinematics : the sign of the intensity probe is also examined. Next, the source is taken to be a translating or rotating dipole of oscillating force F(t). Both stationary and moving dipole models are used to investigate the typical sound field generated by a rotating disk.

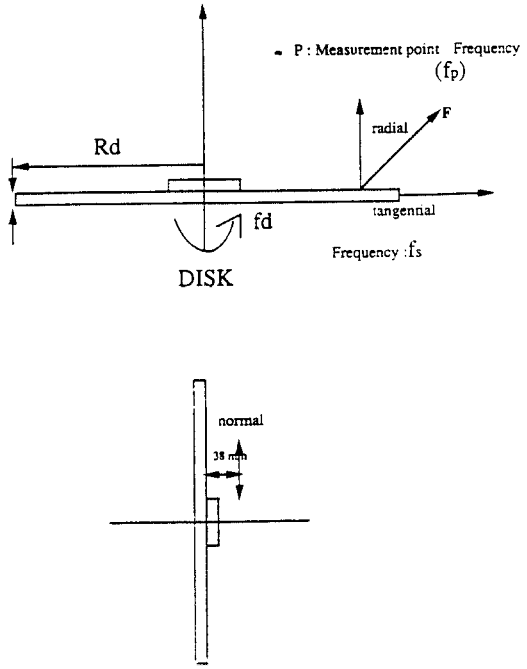

Fig. 1. Schemmatic diagram for acoustic source of rotating disk.

These models are then applied to the idling saw problem and predictions are compared with measured intensity data.

The generic rotating disk model considered in this study is applicable to the rotary cutters such as a saw, disk drives, air moving devices, and other rotating machinery. The following assumptions are made.

(1) The disk rotational speed f_d is constant and subsonic, i.e. $M_d=V_d/C_o=2\pi f_d R_d/C_o<1$.

(2) The acoustic source S is a single dipole induced by the periodic vortex shedding[9-11]. Accordingly, the source is located near the edges, i.e. $R_s=0\{R_d\}$.

(3) The single source may also be given by a combination of N identical but uncorrelated sources distributed around edges. The single net source could then be moved to the origin 0.

(4) The source is modeled as an oscillating sphere of radius a : this source may be compact especially at low frequencies, i.e. $k_s a=2\pi f_s/C_o=2\pi/\lambda_s$.

(5) The source may be stationary or moving : both cases will be considered.

(6) Only the free acoustic field is considered;

(7) The measurement or observation field point P is stationary. Further it is assumed that the intensity probe does not disturb the acoustic field.

The following there coordinate systems are used : Cartesian(x,y,z) for translating sources analysis and field vector measurements, cylindrical(R, ϕ, ζ) for the kinematic and dynamic analyses of the rotating sources, and spherical(r,θ,φ) for the free sound radiation study.

2.1.2 Oscillating Sphere Model

The point dipole model as given by the first two theories will be used in this report ; it will also be compared with the Curle-Lighthill theory[12] which has been applied to the disk acoustics problem. Chief advantage of the oscillating sphere model is the prediction of neau field and its adaptability t the rotating source model. A harmonically oscillating sphere of radius "a" exerting a sinusoidal force $F_z \exp(j\cdot\omega_s t)$ in the z direction can treated as a finite harmonic dipole located at the origin, the z axis is the dipole axis. Acoustic pressure p and radial velocity u for free field spherical radiation in(r,θ,φ) coordinates are as follows for $r\geqq a$:

$$p(r,\theta,t) = \frac{\tilde{F}_z}{4\pi}\frac{(1+jk_s r)}{r^2}\frac{\cos\theta}{(1+jk_s a)}e^{j[\omega_s t - k_s(r-a)]} \quad (1)$$

$$u_r(r,\theta,t) = \frac{\widetilde{F}_z}{4\pi\rho_o C_o}\frac{2k_s r + j(k_s^2 r^2 - 2)}{k_s r^3}$$
$$\frac{\cos\theta}{1 + jk_s a} e^{j[\omega_s t - k_s(r-a)]} \quad (2)$$

Mean square pressure $\langle p^2\rangle_t$ and the resistive acoustic intensity in the radial direction I_r are :

$$<p^2>_t = P_{rms} = \frac{1}{2}Re[\widetilde{p}\cdot\widetilde{p}^*] \quad (3)$$

$$I_r(r,\theta,\omega_s) = \frac{1}{2}Re[\widetilde{p}\cdot\widetilde{p}^*] = \frac{<p^2>_t}{z_o}\frac{k_s^2 r^2}{(1+k_s^2 r^2)} \quad (4)$$

The resistive intensity in the θ direction is zero. The sound power W radiated at ω_s is given by the product of spatially averaged I_r and the radiation surface area A.

$$W(\omega_s) = <I_r>A = \frac{|\widetilde{F}_z|^2}{24\pi a^2\rho_o C_o(1+k_s^2 a^2)} \quad (5)$$

The source is a point or compact dipole if $k_s a \ll 1$.

2.1.3 Acoustic Intensity of Near Field in Disk

The acoustic near field condition is given by $k_s r \ll 1$ or $r \ll \lambda_s$. Accordingly, Equations(1-4) show that in the near field for $r \geq a$,

$$p \approx \frac{\cos\theta}{r^2},\ u_r \approx \frac{\cos\theta}{r^3}$$

$$I_r \approx \frac{\cos\theta}{r^2},\ \widetilde{z}_r = \frac{\widetilde{p}}{\widetilde{u}_r} = \frac{1}{2}jk_s\rho_o C_o r \quad (6)$$

We note that the field is very reactive as the radiation impedance z is purely imaginary, and that the pressure and velocity gradients are very steep. Further, I_r is not equal to $\langle p^2\rangle_r / \rho_0 C_0$. Also, $I_r = \langle p^2\rangle / \rho_0 C_0$ which froms the basis of far field sound source power measurements as I_r and W can be easily related to $\langle p^2\rangle_t$.

2.2 Basic Theory of Acoustic Intensity

In an elasto-acoustic system, the acoustic intensity is a vector quantity defined as a product of the acoustic pressure and the corresponding particle velocity at a given point. When there is no flow, the one dimensional equation of motion is defined as follows[13]

$$\rho\frac{\partial u(t)}{\partial t} + \frac{\partial p(t)}{\partial r} = 0 \quad (7)$$

where ρ is the density of air, u(t) is particle velocity in the r-direction.

the acoustic pressures $p_1(t)$ and $p_2(t)$ are measured at two closely-spaced points in the r-direction. The gradient of acoustic pressures is approximately represented as

$$\frac{\partial p(t)}{\partial r} = \frac{p_2(t) - p_1(t)}{\Delta r} \quad (8)$$

where r is the distance between two points where the acoustic pressures are measured. The approximate particle velocity is

$$u(t) = -\frac{1}{\rho}\int_{-\infty}^{t}\frac{\partial p(t)}{\partial r}dt$$
$$= -\frac{1}{\rho\Delta r}\int_{-\infty}^{t}\{p_2(t) - p_1(t)\}dt \quad (9)$$

and the acoustic pressure p at the center of two points can be approximated as $p(t)=\{p_1(t)+p_2(t)\}/2$. Therefore the acoustic intensity I becomes

$$I = \lim_{T\to\infty}\frac{1}{T}\int_{-\infty}^{\infty} u(t)\cdot p(t)\,dt = \langle p(t)\cdot u(t)\rangle$$

$$= -\frac{1}{\rho\Delta r}\left\langle \left\{\frac{p_1(t)}{2}+\frac{p_2(t)}{2}\right\}\int_{-\infty}^{t}\{p_2(t)-p_1(t)\}\right\rangle \tag{10}$$

where ⟨ ⟩ denotes a time average. Because the process is stationary and ergodic $\langle p_1(t)/p_2(t)dt\rangle$ becomes zero, and using the relation of $\langle p_1(t)/p_2(t)dt = -p_2(t)/p_1(t)dt\rangle$, the acoustic intensity of equation (10) can be rewritten as follows

$$I = -\frac{1}{\rho\Delta r}\left\langle p_1(t)\int_{-\infty}^{t} p_2(\tau)\,d\tau\right\rangle \tag{11}$$

By computing the Fourier transform of equation (11), acoustic intensity $I(f_1-f_2)$ in frequency domain is expressed as

$$I(f_1-f_2) = -\frac{1}{2\pi\rho\Delta r}\int_{f1}^{f2}\frac{\mathrm{Im}\{G_{12}(f)\}}{f}\,df \tag{12}$$

where Im is the imaginary part of a complex number and $G_{12}(f)$ is the cross spectral density function of the acoustic pressures at the two points.

Hence acoustic intensity can be determined by measuring the imaginary part of the cross-spectrum between the pressures p_1 and p_2 measured at closely-spaced points. In this paper, a 2-channel FFT analyzer was used to compute the acoustic intensity in the frequency domain.

Ⅲ. Experiment

3.1 Experimental Apparatus and Method

An idealized experiment seemed to offer most promise in the study of the feasibility of using acoustic intensity measurements on a circular saw. The acoustic intensity of the moving noise source in a circular saw was measured to idenify the source characteristics. The acoustic intensity was measured in a rectangular semi-anechoic chamber (3.3m×2.0m×2.3m), with a cut-off frequency of about 300 Hz, as shown in Fig.2 The variable speed drive motor was located outside the room to minimize its contribution to room noise. the acoustic intensity was measured in three directions at points in front of the sawblade(Fig.3). The acoustic intensity measurement surfaces were 38 mm away from the sawblade.

3.2 Measuring Systems and Data Processing Techniques

Acoustic intensity measurements were made at the predetermined grid points . The distance between the grid points was precisely kept at 50mm. Two 3.2mm Bruel & Kjaer(B&K 4138) microphones in a side-by-side configuration 13mm

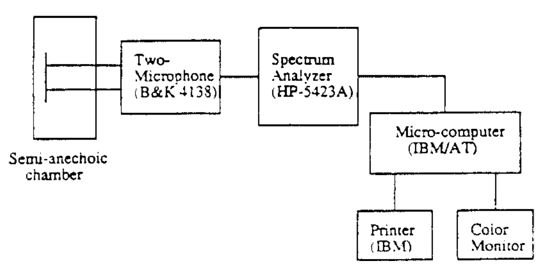

Fig. 2. Schematic diagram of experimental set up for noise source identification of a circular sawblade

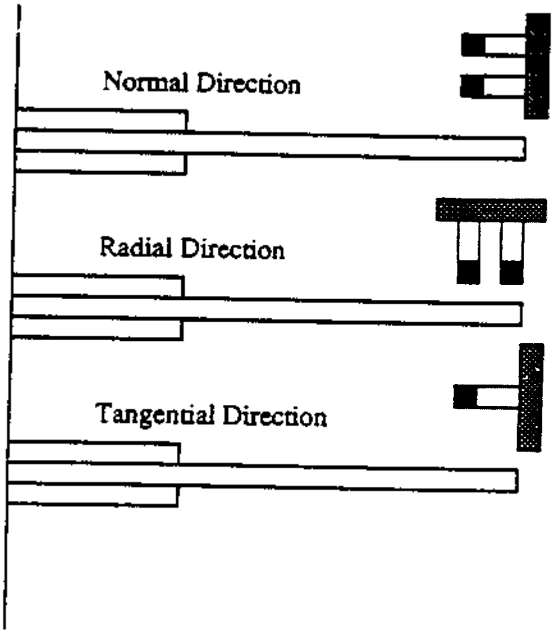

Fig. 3. Three Directions of Measurement for Acoustic Intensity in a CirCular Sawblade.

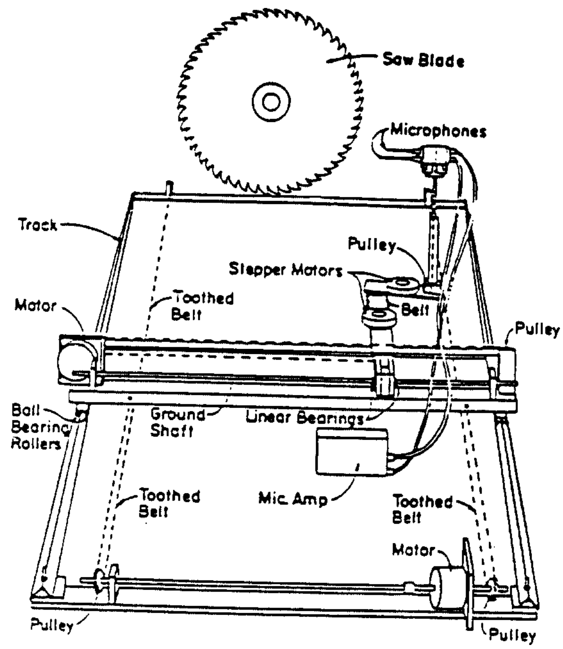

Fig. 5. Microphone positioning system.

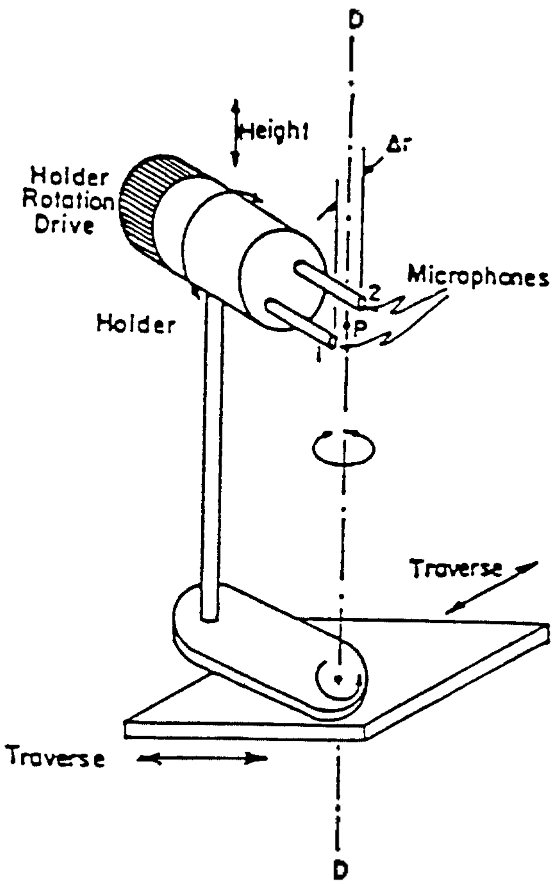

Fig. 4. Two microphones mounted in a cylinderical holder.

apart were used to measure the acoustic intensity (Fig.3). The microphones were mounted in cylindrical holder as shown in Fig.4. The holder position about its axis of symmetry was controlled with a rotation drive, and the hoeder was rotated about the axis D-D to change the direction of acoustic intensity. In this experiment, the height of the measurement point was set at the height of the axis the sawblade. The height of measurement point P was adjustable. Measurement point was positioned parallel to the plane of the disk with a motor driven traverse(Fig.5). Acoustic intensity spectra were computed from cross-spectra density measurements on two-channel FFT analyzer(HP 5423A). At each measurement point 512 averages of the spectra were obtained in a 6.25 Hz bandwidth in the frequency range 250Hz to 1600Hz. The lower and upper frequency ranges were limited by the microphone spacing. the spectra at each measuring points in each of three directions were the average of 512 spectra with the microphones positions interchanged after every 256 samplings to compensate for differences in phase between the two microphones. Each acoustic intensity, computed form this data, is the vector component of sound power in one of the three particular directions. The moving source was identified from these data. A microphone positioning system controls the position of the microphone relative to the sawblade surface. The measurement points were 25 points and 49 points in front of sawblade as shown in Fig.6 and Fig.7. In order to identify noise source mechanism, these results were shown by contour, 3-D and intensity vector flow plots.

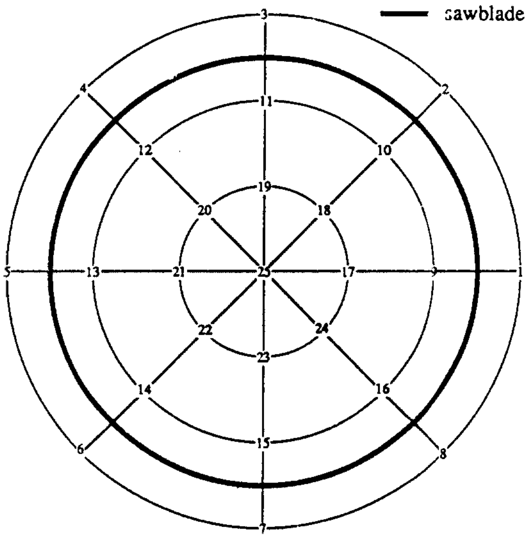

Fig. 6. Measuring point in a circular sawblade for verification of acoustic intensity at the same radius in case of 25 points.

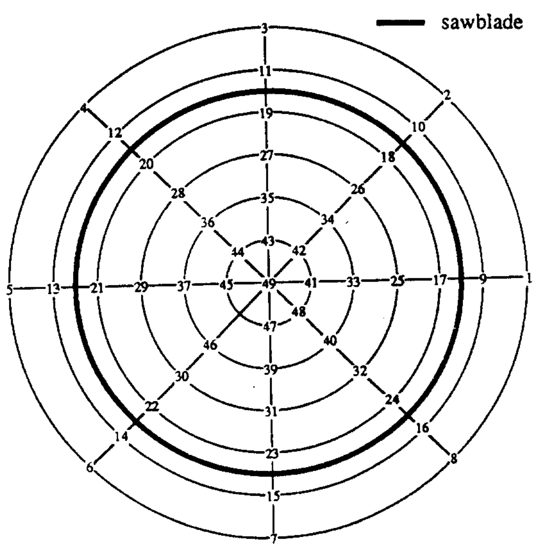

Fig. 7. Measuring point in a circular sawblade with diameter 228mm, 72 teeth and damping.

Ⅳ. Results and Considerations

4.1 Acoustic Intensity radiated from a Circular Sawblade

In this experiment, microphones were moved in measurement positions automatically, but it took about very long time to record the spectra in three directions at a point. If the measured acoustic intensity spectra in tangential, radial, and normal direction at 900rpm were identified by the mechanism of radiation from the sawblade, measuring time would be saved. With same source receiver distances of tangential, radial and normal directions on the sawblade the spectra of acoustic intensity were obtained as shown in Fig.8. This figure shows the representative waterfall plots for the same radius range and each direction of measurement on 25 points. All the spectra have the same scale with the maxima frequency. Therefore, the measurement taken at one point could replace another points at the same distance to reduce measurement time. The spectra of acoustic intensity at radial and normal directions were identical to each same radius as shown in Fig.8.

4.2 Characteristics of Acoustic Intensity due to Rotating Speed

Fig.9 shows such waterfall plots of acoustic intensity at each directions of measurement taken during the variations of rotating speed. All spectra have the same scale, with the maximum height plotted equal to the value of the highest peak, which is at the lowest runout frequency at 900rpm. As the rotating speed increased, these response

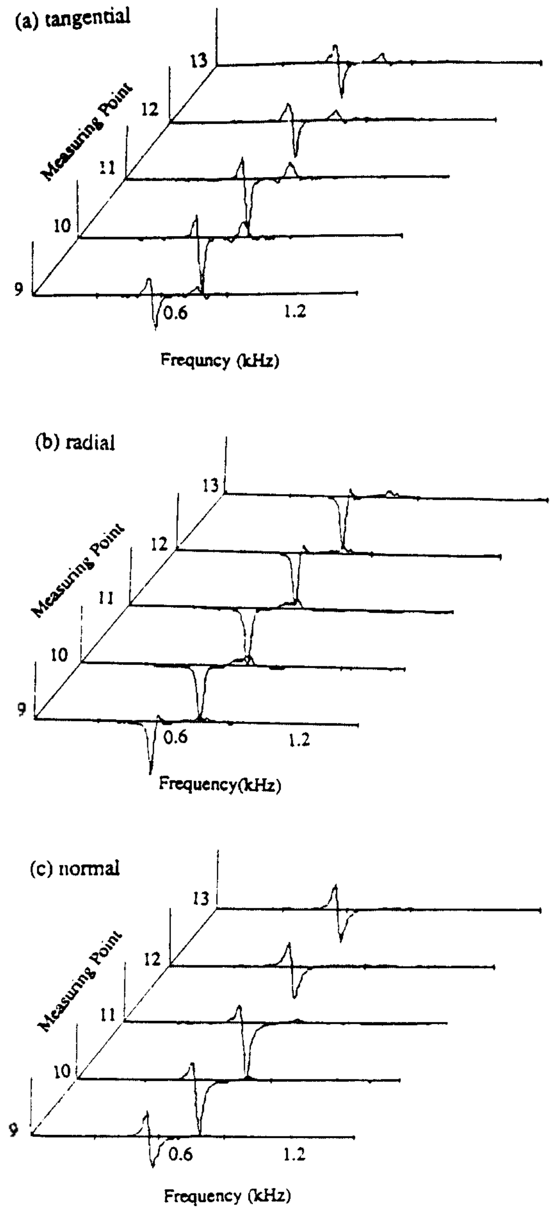

Fig. 8. Waterfall plot of circular sawblade at 900rpm of each direction of measurement on the same radius.

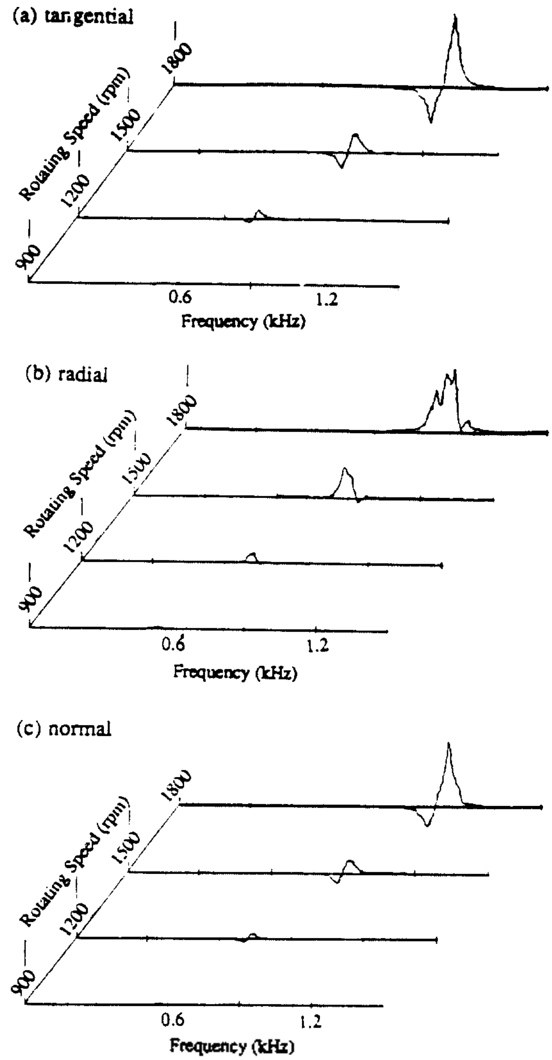

Fig. 9. Acoustic intensity spectra for sawblade at various rotating speed.

and peak frequencies of acoustic intensity also increased at the peak frequency. In the other hand, the spectra of acoustic intensity due to change of measurement of sawblade at the same rotating speed is shown in Fig.10. The level of acoustic intensity had the maximum in the vicinity of rim. Also, the responses of acoustic intensity at each directions of measurement shows the similar characteristics. Fig.11 shows the responese of acoustic intensity in each directions of measurement at same measuring points. The level of acoustic intensity in tangential and normal measurements directions had values from negative positive according to increase of the rotating speed. Specially, the response in radial direction of measurement only has positive level of acoustic intensity. The results mean that the acoustic intensity of radial direction has only source without sinking.

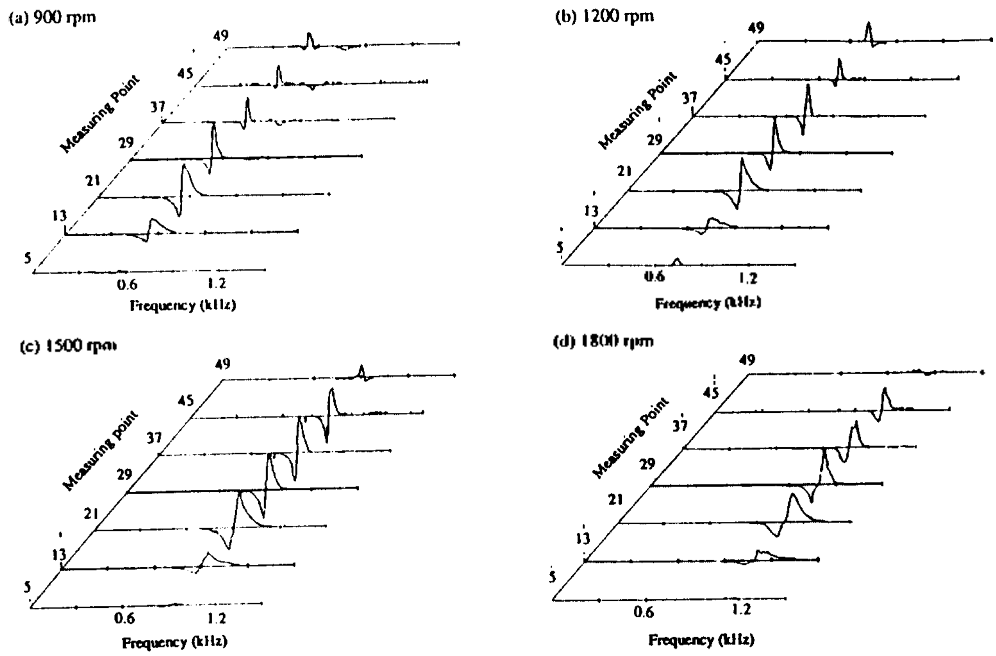

Fig. 10. Comparisons of response of racoustic intensity due to changing ofmeasuring points at tangential direction of micriphone poistion.

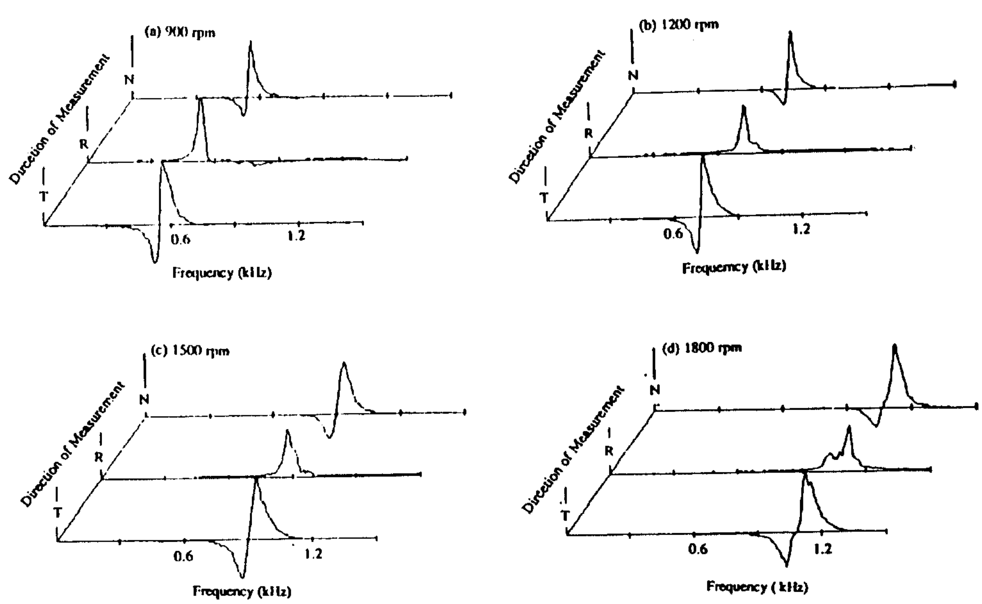

Fig. 11. Acoustic intensity spectra of each measuring direction and rotating speed at the same measuring point(No.17).

4.3 Noise Source Ranking due to Spatial Averaging of a Circular Sawblade

The use of acoustic intensity rather than sound pressure to determine sound power means that measurements can be made in situ, with steady background noise and in the near field of machines. The sound power is average normal intensity over a surface enclosing the source multiplied by the surface area. We can choose any enclosing surface as long as no other sources or sinks(abs-

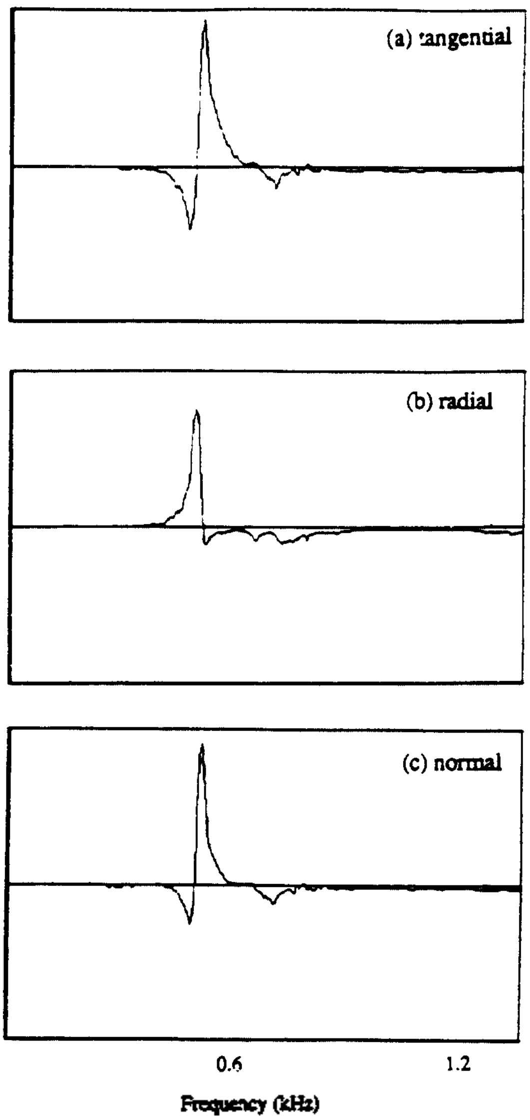

Fig. 12. Acoustic intensity spectra for ranking source inentification of spatial averaging in a circular sawblade at ratating speed 900rpm.

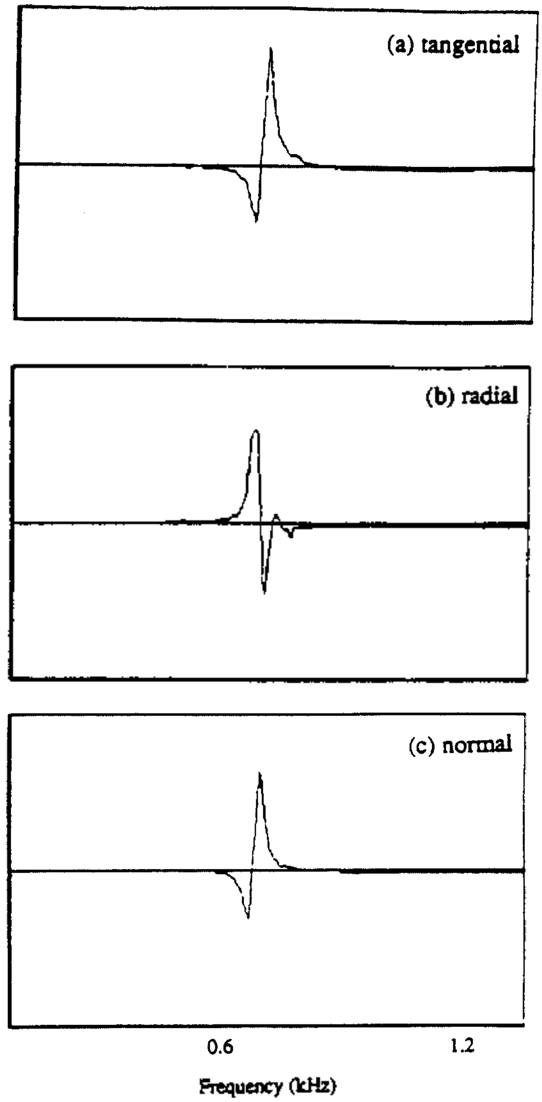

Fig. 13. Acoustic intensity spectra for ranking source inentification of spatial averaging in a circular sawblade at ratating speed 1200rpm.

orbers of sound) are present within the surface. After a surface has been defined, we need to spatially average the intensity values measured normal to the surface. To obtain an average intensity value from each side, one of two spatial averaging techniques can be used. In this study, an intensity surface covering the measuring object is divided up into small segments, and the acoustic intensity in each segment is measured. The results were averaging to find the source location and

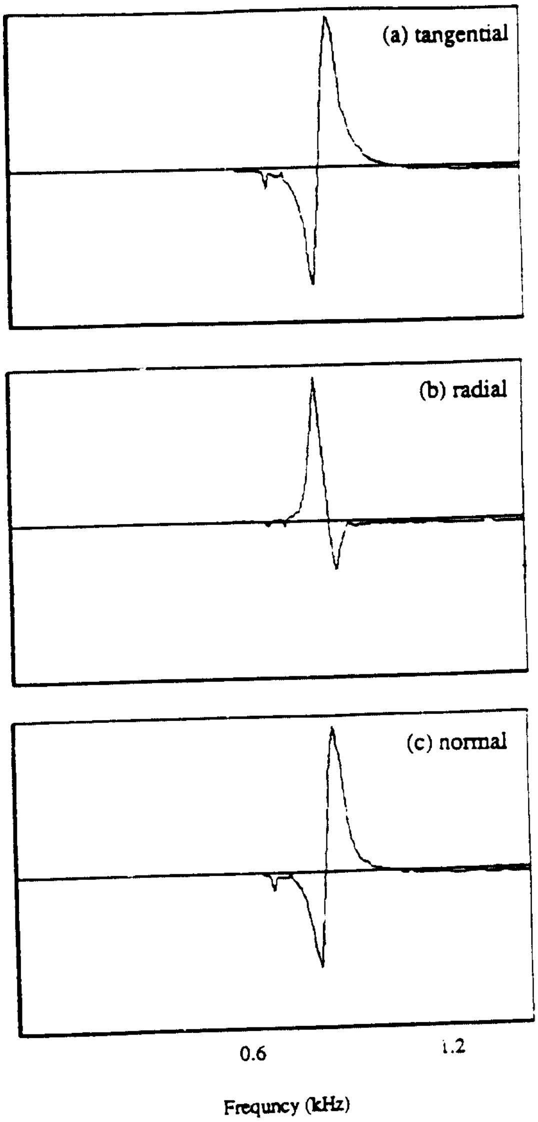

Fig. 14. Acoustic intensity spectra for ranking source inentification of spatial averaging in a circular sawblade at ratating speed 1500rpm.

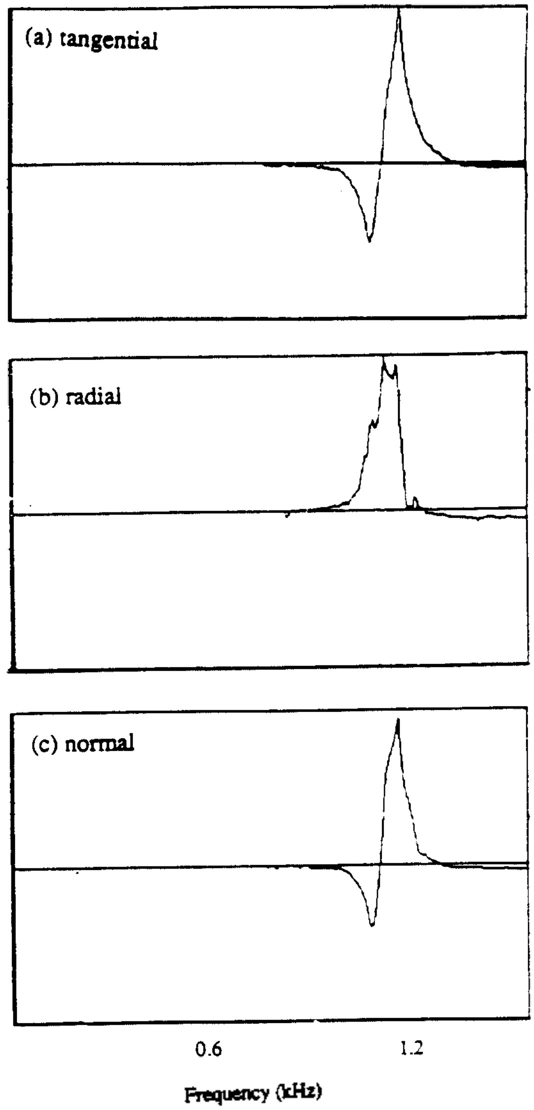

Fig. 15. Acoustic intensity spectra for ranking source inentification of spatial averaging in a circular sawblade at ratating speed 1800rpm.

source ranking. Fig.12-Fig.15 show the results averaged spatial at radius rotating speeds and directions of measurement. By these results, the comparisons between theoretical and experimental frequencies of moving source in a circular sawblade are shown in Table 1.

4.4 Acoustic Radiation Pattern of a Circular Sawblade by Contour and 3-D Plots

Every noise control problem is first of all a problem of location and identification of the source. Acoustic intensity measurement offers several ways of doing this which have considerable advantages over previous techniques. Contour and 3-D plots give a more detail picture of the sound field generated by a source. Several source and or sinks can then be identified with accuracy. In this study, lines of equal intensity can be drawn by interpolating(Cubic Spline method) and joining up points of equal intensity. They are sometimes called iso--intensity lines and they can be drawn either at single frequencies. A separate plot can be made for negative-going intensity which can be used to locate sinks of sound energy. The same data can be used to generate 3-D plot which provides easy visualization of the sound field generated by a source. We can, of course, also make contour maps and 3-D plots with acoustic intensity measurements. But, intensity maps can be made in the near field where the correlation between the measured intensity levels and the source position is greater. Due to the change of measuring directions, the acoustic intensity is shown in all cases. Fig.16-Fig.18 show contour maps. Specially Fig. 17 shows that the acoustic intensity had the sou-

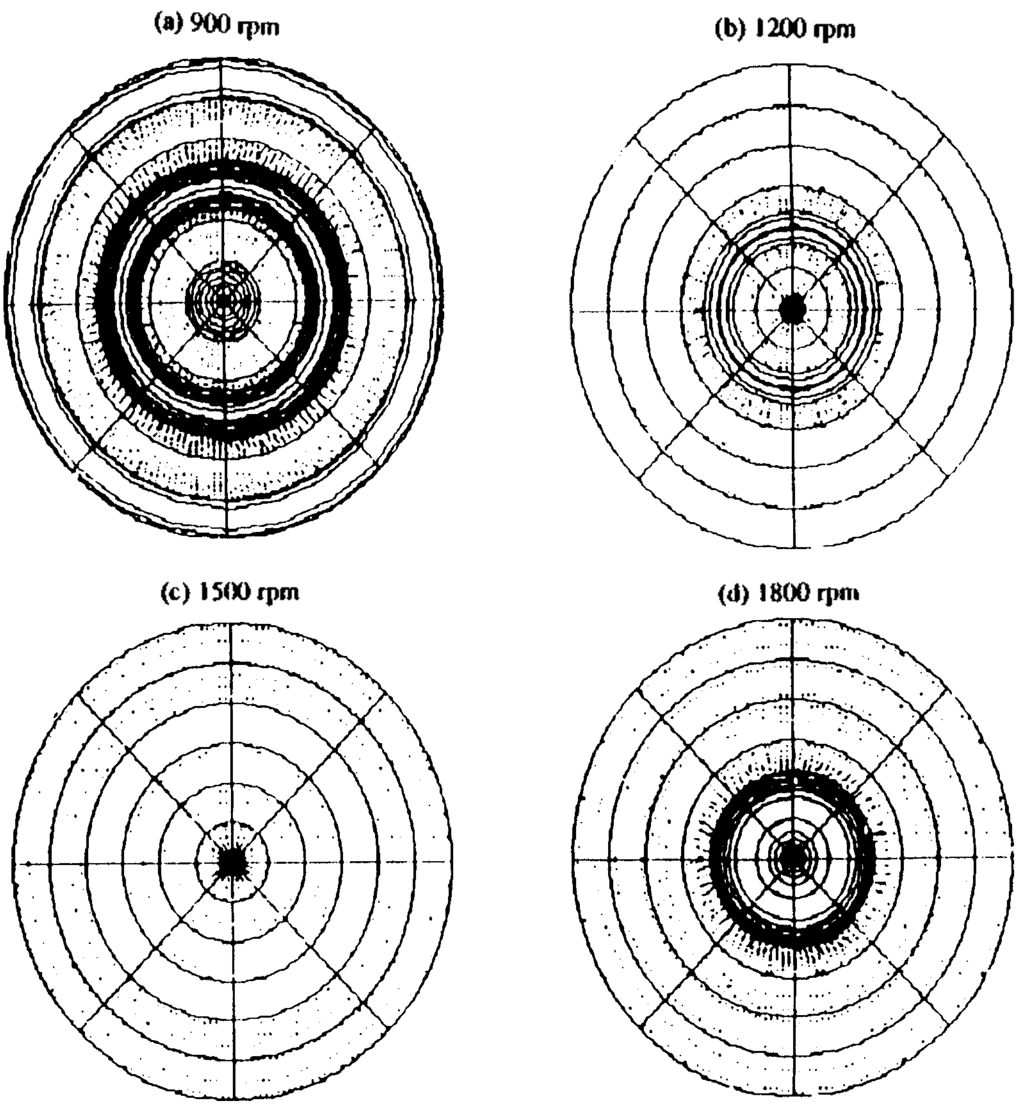

Fig. 16. Contour plots of circular sawblade at tangential measurement direction of microphone position due to change of rotating speed.

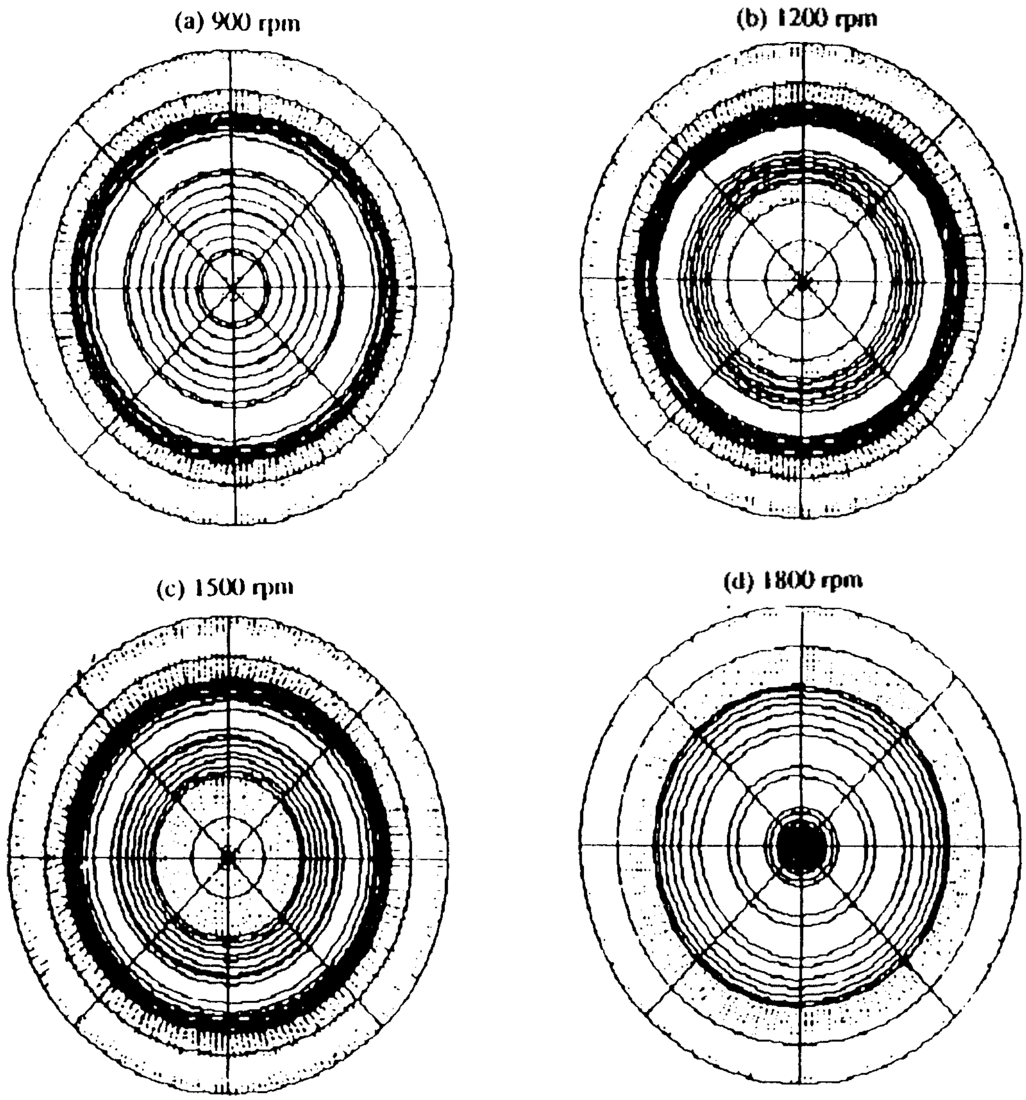

Fig. 17. Contour plots of circular sawblade at radial measurement direction of microphone position due to change of rotating speed.

rces in the vicinity of the rim. All figures are drawn to the same scale for comparison. The comtour maps are oriented with rotating speed toward different patterns. When the rotating speed is reduced to poorpm, several things occur. A dominant positive circle contour line appears with near the center of sawblade at tangential direction of measurement. The positive contour line is toward center at tangential direction of measurement but the largest contour line is appeared at rim of sawblade on the radial direction of measurement. When the directions of measurement is normal, the contour is not appeared clearly except at 12 00rpm. Interestingly, this contour pattern is always not on the center thorugh the rotating speed but occurs on a rim.

The acoustic intensity distribution in the circular sawblade is fairly even with acoustic intensity maxima close to the center and rim. The dominant phenomenon are appeared as the rotating speed

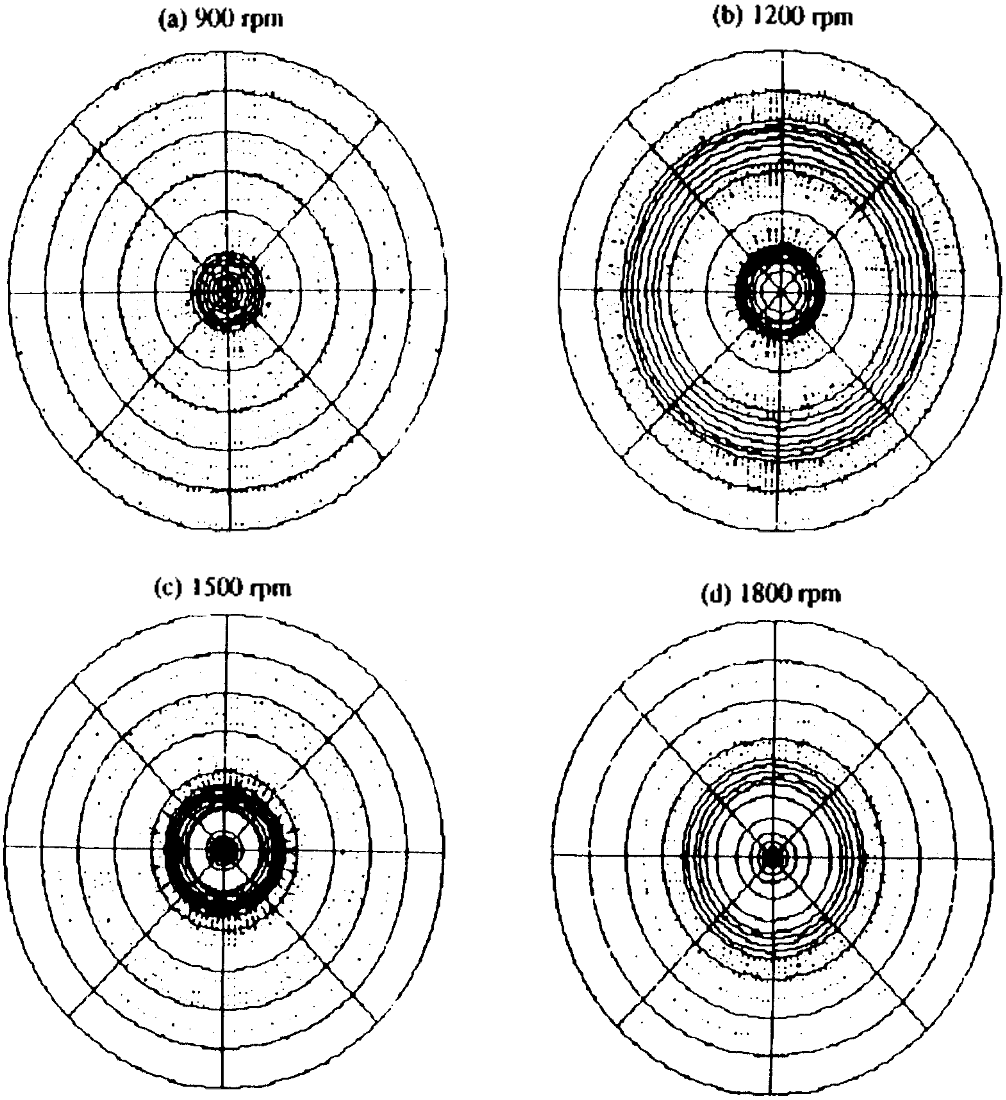

Fig. 18. Contour plots of circular sawblade at normal measurement direction of microphone position due to change of rotating speed.

increases. In fact, the 3-D plots of acoustic intensity are shown the pattern of source at rim(Fig. 19-Fig.21). The most case measured at radial direction(Fig.20) has acoustic intensity on the center of sawblade. The negative value of acoustic intensity occurs at the outside from rim thorugh change of rotating speed. But, at radial measurement direction the pattern of acoustic source is notappeared apparently. Therefore, the noise source is composed of moving andstationary components uniformly distributed at the sawblade rim. The stationary component is given by a number of identical, equally spaced dipoles radiating at a discrete frequency governed by the rim shape and speed. The moving component is produced by the turbulent eddies convecting over the sawblade surface and teeth. This can be modeled via a number of identical radial dipoles rotating at a velocity bounded by the rim speed. From the results mentioned above, it can be seen that the

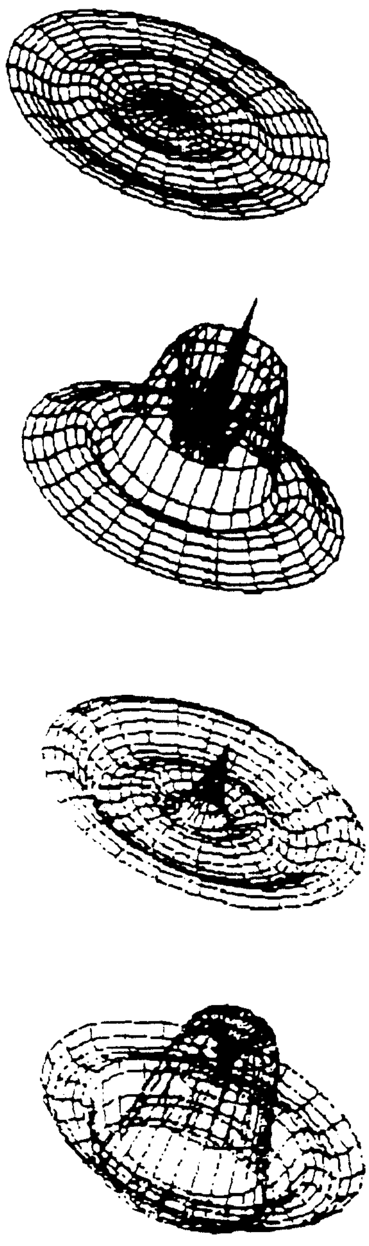

Fig. 19. 3-D plots of cirular sawblade at tangential direction of measuremnt due to change of rotating speed.

Fig. 20. 3-D plots of cirular sawblade at normal direction of measuremnt due to change of rotating speed.

source of sawblade should have to be modeled as spherical source.

4.5 Acoustic Intensity Vector of a Circular Sawblade

Vector intensity measurements have been applied to many problems in areas such as room acoustics, musical acoustics, diffractions, etc. As sound source with a complicated near field in a circular sawblade is considered, the circular sawblade was rotated toward counter clockwise with motor outside of anechoic chamber. Fig.22 shows a plot of the intensity vectors parallel to the sawblade, measured

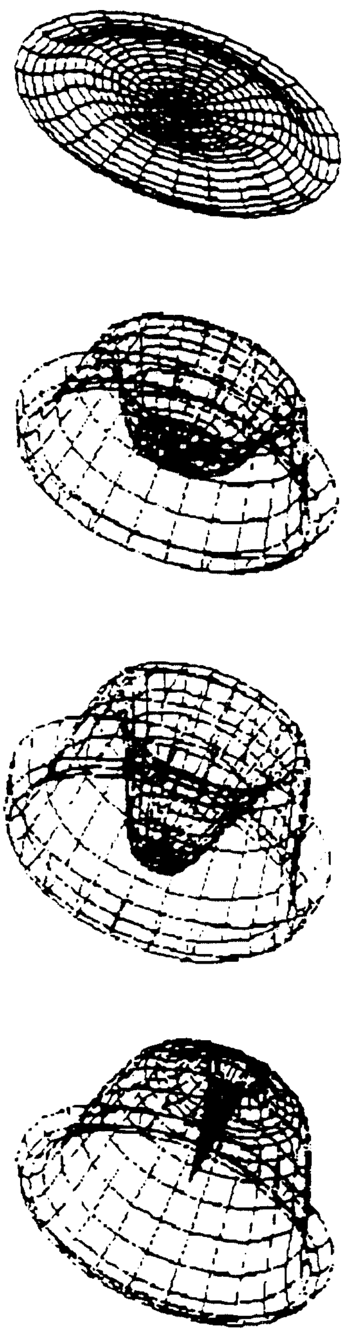

Fig. 21. 3-D plots of cirular sawblade at radial direction of measuremnt due to change of rotating speed.

at 49 points close to surface. Arrow length is proportional to the intensity, and it shows the direction of flow. It can be seen that the origin

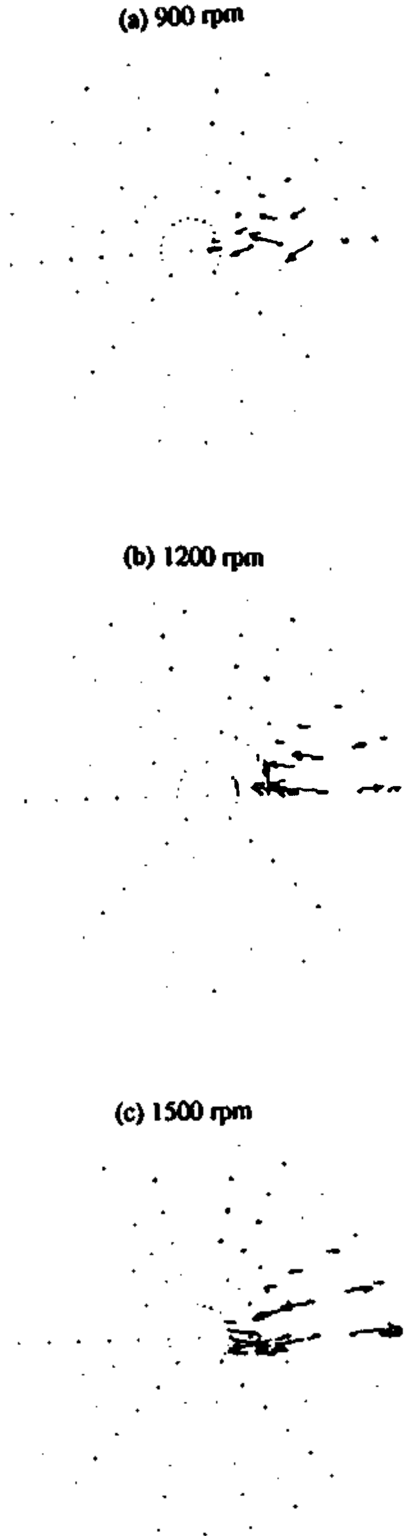

Fig. 22. Acoustic intensity vector flow due to rotating speed for tangential-radial plane.

of te intensity flow closely matches the position of the rim in a circular sawblade and also exists on the center. It can be also seen that the acoustic intensity flows toward clockwise in spite that the rotating direction is counter clockwise. Therefore, the moving noise source is produced by the turbulent eddies convecting over the center of sawblade and teeth. Thus a vector intensity mapping of the near field makes it possible to very precisely locate the points where the intensity is entering the system and identify the major source areas. In this vector plots, the source location has been found nom mapping of the tangential-radial plane inte-

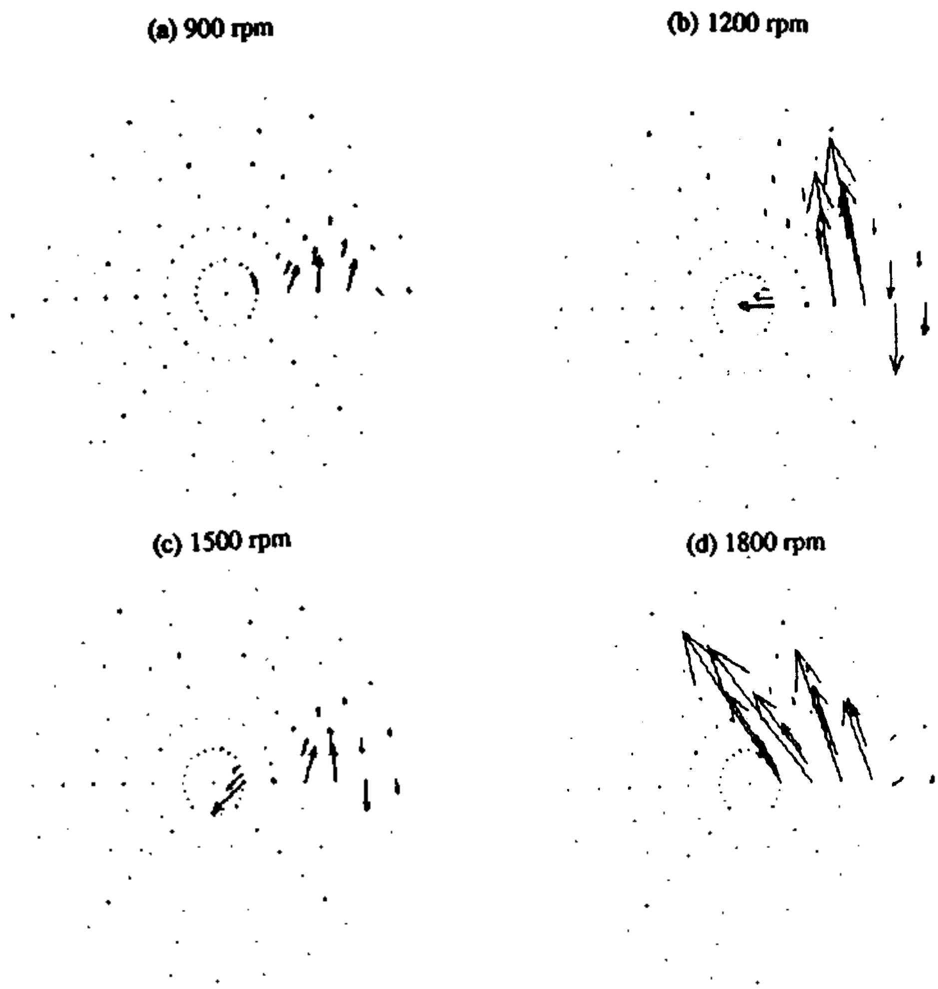

Fig. 23. Acoustic intensity vector flow due to rotating speed for radial-normal plane.

nsity vector component only. The presentation of a circular sawblade surface, as for example a computer display, is difficult and different, which has been chosen here to present the normal intensity our of the surface of sawblade separately as a 3-D plot. The results are shown in Fig.23. The major source is also easily identified as the rim of the sawblade with the result at radial-normal plane. A near field measurement, as described previously, around this can then eventually be used to localize the source more precisely.

V. Conclusions

The experiments described show conclusively that the turbulent phenomena is a significant source mechanism, such as the stationary oscillating sphere model, producing the rotating dipole noise source. The feasibility of the source identification in a circular sawblade has been demonstrated as contour and 3-D plots. Furthermore, the acoustic intensity vecotr is shown more closely the mechanism of noise source and given the projected acoustic intensity in a tangential-radial plane and normal to the surface of sawblade.

In the future, the theoretical analysis of rotating disk aero-acoustic sources should be studied more to identify the source and quantify source locations, strength, and distribution. Experiment should be carried out in the following sequence : (i) identification of well known dipole source,(ii) a circular disk without any teeth, (iii) a disk with and without slots or damping treatment.

The measuring procedure may be computer manipulated, and positioning of the probe may be done manually or by a measuring robot for greater speed and accuracy.

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