LASER REMOTE DETECTION FOR
PARTICLE CONCENTRATIONby SHUJI FUJII*, KWANG YOUNG KIM**, TATSUYA
SUNAGAWA***, and ICHIYA HAYAKAWA**** Mem-
bers of A. I. J.

Introduction

From the viewpoint of contamination control in clean rooms, the authors have pointed out that it is necessary to decrease the number of particles reaching a specific object as well as their adhesion to the object rather than to reduce particle concentration in the whole clean space. Therefore, it is very important to make direct measurements of particle behavior and concentration near the object without field disturbance. The authors have presented in the previous paper¹⁾ one of the techniques of laser remote detection for analysis of particle behavior, which consists of a video and image processing system.

The authors developed a new remote laser particle detection system in order to cover weak points of commonly used optical particle counters and to make direct measurements of particle concentration without field disturbance. The new system introduces a photomultiplier and a pulse height analyzer. By shooting a He-Ne laser beam with a scanner into the measuring space, scattered light by an existing particle is detected by the photomultiplier through lenses and a slit, and then converted to an electric pulse. After amplification, the pulse is classified by using the pulse height analyzer. Particle concentration is estimated by the pulse count and the measuring space volume. The measuring space volume of the system is theoretically calculated as a function of laser beam diameter, scanning frequency, slit sizes, photo detection angle and magnification ratio. By using both the previous and the present system, it is possible to make more detailed investigations on particle concentration distribution and behavior.

This paper presents the outline of the new system with measuring principle and characteristics. Characteristics of the system are evaluated through comparison with a currently used optical particle counter. Relations are observed between concentration values obtained by the two systems as functions of scanning frequencies and slit heights. Correlations are also established between concentration values obtained by the two systems.

Nomenclature

- f : scanning frequency (Hz)
- θ : photo detection angle ($^{\circ}$)
- α : scanning angle (rad)
- d : distance from scanner to measuring space (m)
- m : magnification ratio (measuring space/slit place)(-)
- w : laser beam diameter at measuring space (m)
- l : slit width (m)
- h : slit height (m)
- D : laser beam scanning range (m)
- L : detectable width of measuring space (m)
- H : detectable height of measuring space (m)
- t : measuring time (s)
- V_s : measuring space volume per second (m^3/s)
- V : measuring space volume per minute (m^3/min)
- n : particle concentration (particles/ m^3)

* Associate Professor of Tokyo Institute of Technology, Dr. Eng.

** Graduate student of Tokyo Institute of Technology, M. Eng.

*** Member of Nippon Telegraph and Telephone Corporation, M. Eng.

**** Professor of Nihon Institute of Technology, Ph. D

(Manuscript received April 10, 1987)

Nt : particle count per t seconds (particles)
 U : airflow velocity (m/s)
 U_x : X component of airflow velocity (m/s)
 U_y : Y component of airflow velocity (m/s)
 ϕ : angle between airflow and laser beam scanning area ($^\circ$)
 U_{rs} : relative scanning velocity at measuring space (m/s)
 U_s : scanning velocity of laser beam ($=2fda$)(m/s)
 L_s : single scanned length of air in measuring space (m)

Remote Laser Particle Detection System

The newly developed remote laser particle detection system consists of three parts : light source, photo detector and pulse height analyzer. Fig.1 shows the principle of the new system and Fig.2 shows the components of the system. A He-Ne laser (power 25 mW, beam diameter about 1.3 mm, mode TEM₀₀) is used as a light source. After the coherent fringe around the He-Ne laser beam is eliminated by a circular slit of diameter 2.0 mm, the laser beam is focused by a convex lens of focal length 300 mm for intensifying its power density. The measuring space is shot by the laser beam with a vibrating mirror (scanner). Existing particles in the measuring space scatter light as pulses because the laser beam shoots the particles with scanning. The scanning frequency and the wave form of the scanner are controlled by a scanner driver and a function generator.

The scattered lights are detected by a photomultiplier through lenses and a slit located at a distance of about 400 mm from the measuring space. The measuring space can be defined by the lens, the rectangular slit and the laser beam. The scattered light pulses are converted to electric pulses by the photomultiplier. After amplification, the pulses are sent to the pulse height analyzer and the microcomputer. The pulse height analyzer is used for the characteristics of pulse counts to height and pulse counts along time. Particle concentration and size are estimated by the pulse counts and height.

Fig. 1 Principle of the remote laser particle detection system

Fig. 2 Components of the new remote laser particle detection system

Measuring Space Volume

The measuring space volume of the system is theoretically calculated as a function of laser beam diameter, scanning frequency, slit sizes, photo detection angle and magnification ratio, as shown in Fig. 1. The space volume measured in one second, V_s , is calculated by Eq. 1 on condition that the effect of airflow is negligible.

$$V_s = 2 \cdot f \cdot m^2 \cdot l \cdot h \cdot w / \sin \theta \quad (1)$$

Particle concentration n in the measuring space is obtained from Eq. 2.

$$n = \frac{N_t}{V_s \cdot t} \quad (2)$$

Effect of Airflow

When airflow velocity is U m/s and the angle between airflow and laser beam scanning area is ϕ as shown in Fig. 3, airflow velocity components U_x , U_y are described by Eq. 3 and Eq. 4.

$$U_x = U \cdot \cos \phi \quad (3)$$

$$U_y = U \cdot \sin \phi \quad (4)$$

The relative scanning velocity at the measuring space, U_{rs} , is given by Eq. 5 and Eq. 6.

$$U_{rs} = U_s - U_x \quad (5)$$

$$U_{rs} = U_s + U_x \quad (6)$$

Single scanned length of the air in the measuring space, L_s , which corresponds to the measuring space volume of the system, is estimated from Eq. 7.

$$L_s = \frac{1}{2 \cdot f} \{ ((U_s - U_x)^2 + U_y^2)^{1/2} + ((U_s + U_x)^2 + U_y^2)^{1/2} \} \quad (7)$$

The errors caused by airflow can be estimated by the differences between the scanned length of the air in the measuring space. Fig. 4 shows scanned length of the air in the measuring space per unit time for three different airflow velocities and two different angles as a function of scanning frequency. Fig. 5 shows particle concentration normalized by concentration when airflow velocity is 0.0 m/s. Scanned length of the air in the measuring space increases as airflow velocities rise and also as the angle between airflow direction and laser beam scanning area approaches 90° . Therefore calculated scanned length of the air in the measuring space is greater than the real relative

Fig. 3 Schematic diagram showing laser beam scanning trace as well as airflow velocity and direction

Fig. 4 Scanned length of the air in the measuring space as a function of scanning frequency for different airflow velocities and directions

scanned length and hence particle concentration value becomes a little higher than the real one. However, the effect of airflow becomes negligible as the laser beam scans more frequently. Because of above mentioned effect, scanning frequency f , detectable width of measuring space L and laser beam scanning range D are set at 100 Hz, 2.5 mm and 11.0 mm respectively.

Performance of the System

The performance of the remote laser particle detection system is evaluated through comparison with a currently used optical particle counter. Relations are observed between concentration values obtained by the two systems as functions of scanning frequencies and slit heights. Correlations are also established between concentration values obtained by the two systems.

Fig. 6 shows a schematic diagram of the experiment used for comparison between the remote laser particle detection system and a currently used optical particle counter. Airflow velocity is set at 0.6 m/s in a vertical laminar airflow type clean booth. Polystyrene latex (PSL) spheres, 0.410 and 0.796 μm in diameter, are emitted isokinetically from the upper stream. PSL spheres are counted by the two systems at the points 185 mm and 200 mm below the generating position respectively. The experimental conditions of the remote laser particle detection system are described in Table 1. The photo detection angle of the system is set at 9° and scattered light intensity to particle size is described in Fig. 7. The slit size is 2.0 mm $\times$ 0.5 mm. The measuring space volume of the system is $0.063 \times 10^{-3} \text{ m}^3/\text{min}$. Airflow velocity inside the sampling probe of the optical particle counter is 0.59 m/s, which is

Fig. 5 Normalized concentration as a function of scanning frequency for different airflow velocities and directions

Fig. 6 Schematic diagram of the experiment used for comparison between remote laser particle detection system and optical particle counter

Table 1 Experimental conditions of the remote laser particle detection system

scanning frequency (f)	: 100 (Hz)
photo detection angle (θ)	: 9 ($^\circ$)
magnification ratio (m)	: 1.3 (-)
laser beam diameter (w)	: 0.52×10^{-3} (m)
slit width (l)	: 2.0×10^{-3} (m)
slit height (h)	: 0.5×10^{-3} (m)
laser beam scanning range (D)	: 11.0×10^{-3} (m)
detectable width of measuring space (L)	: 2.5×10^{-3} (m)
detectable height of measuring space (H)	: 4.0×10^{-3} (m)
measuring time (t)	: 60 (s)
measuring space volume (V)	: 0.063×10^{-3} ($\text{m}^3/60\text{s}$)

Fig. 7 Scattered light intensity to particle size ($\theta=9^\circ$)

Fig. 9 Concentration as a function of slit height

Fig. 8 Concentration as a function of scanning frequency

Fig. 10 Correlation between concentration values obtained by remote laser particle detection system and optical particle counter

enough to keep isokinetic sampling. The sampling probe length is 600 mm in order to minimize particle deposition errors.

Experiments for examining the relation between concentration values obtained by the two systems as functions of scanning frequencies and slit heights are conducted on condition that the concentration of generated particles is uniform. The laser beam scanning frequencies are changed in the range of 50 Hz to 200 Hz at intervals of 25 Hz ; slit

Fig.11 Relation between concentration values obtained by remote laser particle detection system and optical particle counter

heights are also changed within the 0.5 mm to 2.0 mm range at 0.25 mm intervals. Fig. 8 shows concentrations as a function of scanning frequency. When scanning frequencies are over 100 Hz, good agreement is found through the concentration values obtained by the two systems. When the frequencies become lower than 100 Hz, small differences occur in the two concentrations due to the effect of airflow velocity 0.6 m/s. Fig. 9 shows concentrations as a function of slit height. There is a good agreement between concentration values obtained by the two systems under changes of slit height.

Fig. 10 shows good correlations between concentration values obtained by the remote laser particle detection system and the optical particle counter, when PSL sphere diameter is 0.796 μm . Fig. 11 shows concentration values obtained by the two systems under particle concentration changes. Measurements to concentration changes are carried out during 40 minutes at 1-minute intervals. As the results of the above experiment show, there is a very good correlation between the two systems (correlation coefficient 0.9996). Good agreement is also found between concentration values obtained from both systems. Moreover, the remote laser particle detection system is found to have good sensitivity to rapid changes of particle concentration.

Conclusions

This paper presents an outline of the newly developed remote laser particle detection system consisting of the optical system, photomultiplier and pulse height analyzer and discusses its measuring principle and characteristics.

It is concluded as follows :

- 1) By introducing the remote laser particle detection system, it is possible to solve the problems presented by optical particle counters using sampling probes.
- 2) Good agreement is observed between concentration values obtained by the remote laser particle detection system and an optical particle counter as functions of scanning frequencies and slit heights.
- 3) Good correlation is found between concentration values obtained by the remote laser particle detection system and a currently used optical particle counter.
- 4) The remote laser particle detection system has good sensitivity to rapid changes of particle concentration.

This system may be used for measurements in local spaces, vacuum, high temperature spaces and poisonous gases and for studies on particle adhesion mechanisms. The measuring space volume of the remote laser particle detection system may be enlarged by means of scanning frequency and slit height controls.

The authors express appreciation to Prof. Toshimitsu ASAKURA and Mr. Yasushi KAWASE, Hokkaido University, regarding the development of the remote laser particle detection system.

References

- 1) Fujii, S., Iwase, K., Kim, K. Y. and Hayakawa, I. : Laser Remote Detection for Surface Contamination in Clean Rooms,

Transactions of A.I.J., No. 371, January 1987 (in Japanese)

- 2) Fujii, S., Kim, K.Y., Sunagawa, T. and Hayakawa, I. : Measurements of Particulate Concentration near the Wafers by Laser Remote Detection System, The 4th Symposium on Aerosol Science & Technology (Nagoya Japan), August 1986 (in English)
- 3) Fujii, S., Kim, K.Y., Sunagawa, T. and Hayakawa, I. : Characteristics of Laser Remote Detection System and Measurements of Particulate Concentration Distribution near the Wafers, Summaries of Technical Papers of Annual Meeting of A.I.J., August 1986 (in Japanese)
- 4) Fujii, S., Kim, K.Y. and Hayakawa, I. : Characteristic of a Laser Remote Detection System, Proceedings of 33rd Annual Technical Meeting of Institute of Environmental Sciences (San Jose U.S.A.), May 1987 (in English)

【論 文】

UDC : 628.85

日本建築学会計画系論文報告集
第 379 号・昭和 62 年 9 月

浮遊微粒子濃度測定のためのレーザー遠隔計測（梗概）

正 会 員 藤 井 修 二*
正 会 員 金 光 映**
正 会 員 砂 川 達 也***
正 会 員 早 川 一 也****

1. はじめに

クリーンルームにおけるコンタミネーション・コントロールは、従来の室内気流性状を中心とする浮遊微粒子の空間濃度だけの評価では不十分で、制御対象部位への粒子の到達および付着量を減少させることが必要である。したがって、制御対象部位への浮遊微粒子の輸送や付着機構を解明し、汚染防止対策を講ずることが課題となり、測定対象空間を乱すことなく制御対象部位近傍の浮遊微粒子の挙動および濃度を有効に測定し評価することが必要となる。

筆者らは、既報¹⁾において浮遊微粒子の挙動および付着の計測のために、ビデオシステムと粒子解析器で構成されたレーザー遠隔計測について報告した。本論文では、さらに受光系に光電子増倍管と波高分析器を導入し、空間濃度の計測、特に局所空間における濃度計測に適用し得るレーザー遠隔計測システムを開発し、その概要と計測理論を示すとともに、従来の吸引型粒子計数器との性能比較実験により基本特性を把握したので報告する。

2. レーザー遠隔計測システム

本システムの原理および構成を Fig.1 と Fig.2 に示す。出力 25 mW の He-Ne レーザーからのビームは、

円形スリットおよび平凸レンズを通過した後、スキャナーにより空間中に走査される。測定空間においてレーザービームにより照射された浮遊微粒子は、散乱光を発する。その散乱光をまず望遠レンズでとらえ、次に受光系の矩形のスリットにより限定される空間内の粒子の散乱光のみを広角レンズで捕捉し、光電子増倍管によりパルス信号に変換する。このパルス信号はアンプにより増幅された後、波高分析器により解析される。

本システムの測定空間の体積は、Fig.1 に示すようにレーザービームの直径・走査周波数・スリットの大きさ・受光角度・結像倍率の関数として表され、気流の影響を無視する場合、式(1)により求められる。また、粒子濃度の算出式は式(2)となる。Fig.3 に示すように測定空間の体積に相当する空気の流れ線長は、式(7)から求められ、気流の影響による誤差が推定できる。Fig.4 にレーザービーム走査面に対する気流の角度が 0° および 90° で、気流速度が 0.0, 0.3, 0.4, 0.5 m/s の場合の、走査周波数に対する測定対象空間における空気の流れ線長の数値計算例を示す。また、Fig.5 に Fig.4 と同一条件で求めた走査周波数に対する濃度比を示す。気流速度 0.0 m/s の場合の濃度を 1 とした相対値で表している。空気の流れ線長は、気流速度が大きいほど、またレーザービーム走査面に対する気流の角度が 90° に近いほど長くなり、測定濃度は実際の濃度よりやや高くなる。走査周波数の増加および測定空間の可測幅

* 東京工業大学助教授・工博

** 東京工業大学 大学院生・工修

*** 日本電信電話(株) 社員・工修

**** 日本工業大学 教授・Ph.D

(昭和 62 年 4 月 10 日原稿受理)

の調整によって、気流の影響による誤差を小さくすることができる。そこで本システムでは、走査周波数 (f) を 100 Hz とし、レーザービーム走査幅 (D) 11.0 mm に対し測定空間の可測幅 (L) を 2.5 mm に設定している。

3. システムの性能

従来の吸引型粒子計数器との性能比較実験の概要を、Fig. 6 に示す。実験は垂直整流型クリーンブース内において、気流速度 0.6 m/s のもとで、粒径 0.410 および 0.796 μm の PSL 球を上流より発生させ、発生直下 185 mm の位置をレーザー遠隔計測システムで、また、発生直下 200 mm の位置を吸引型粒子計数器で測定することにより行った。吸引型粒子計数器の概要を Fig. 6 の中に示す。本計数器のサンプリング管内平均流速は 0.59 m/s であり、ほぼ等速吸引とするとともに、管内の粒子損失を少なくするためにサンプリング管長は 600 mm とした。Table 1 にレーザー遠隔計測システムの実験条件を示す。受光角度 (θ)、スリットの大きさ ($l \times h$)、測定空間の体積 (V) は、それぞれ 9° 、 $2.0 \times 0.5 \text{ mm}$ 、 $0.063 \times 10^{-3} \text{ m}^3/\text{min}$ に設定されている。Fig. 7 に受光角度 $\theta = 9^\circ$ の場合の、粒径に対する散乱光強度を示す。

PSL 球の発生濃度を一定とし、レーザー遠隔計測システムの測定条件のうち、レーザービームの走査周波数および受光系の矩形スリットの縦幅を変化させた場合の濃度測定値を調べた。走査周波数は 50 Hz～200 Hz の間を 25 Hz 間隔で変化させ、また、スリットの縦幅は 0.5 mm～2.0 mm の間を 0.25 mm の間隔で変化させた。Fig. 8 に走査周波数と測定濃度の関係を示す。走査周波数が 100 Hz 以上においては、測定濃度はほぼ一致する

が、100 Hz 以下においては気流速度による影響が現れたものと考えられる。Fig. 9 にスリットの縦幅と測定濃度の関係を示す。スリットの縦幅の変化に対し両システムの測定濃度はほぼ一致している。

PSL 球の発生濃度を变化させた場合のレーザー遠隔計測システムと吸引型粒子計数器による濃度測定の実験結果を、Fig. 10 と Fig. 11 に示す。両システムの測定値はほぼ一致し、良好な相関関係を示している。また、レーザー遠隔計測システムは、急激な濃度変動に対しても追従性が高いと考えられる。

4. おわりに

以下に、本研究で得られた成果についてまとめる。

① レーザー遠隔計測システムを用いることにより、サンプリング管を使用する吸引型粒子計数器の問題点の一部が解決された。

② レーザー遠隔計測システムにおける走査周波数およびスリットの大きさの変化は、一定の範囲内では、従来の吸引型粒子計数器の測定値との間に見られる一次的な比例関係に影響を及ぼさない。

③ レーザー遠隔計測システムと吸引型粒子計数器との濃度測定において、両者の測定値はほぼ一致しており、高い相関関係を示す。

④ レーザー遠隔計測システムは急激な濃度変動に対しても追従性が高い。

本システムは従来の粒子計数器では測定し得なかった真空・高温・有毒ガス等の特殊な環境下でも適用できると考えられる。また、走査周波数およびスリットの大きさの調整により、測定対象空間の拡大も可能となる。