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A STUDY ON THE FREQUENCY MODULATION DOPPLER GLOBAL VELOCIMETRY SYSTEM

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ABSTRACT

The principle of the frequency modulation Doppler global velocimetry (FM-DGV) is presented in this paper. A FM-DGV system has been developed, of which a CCD camera was used as the detector to receive scattering light. The system was made up of a narrow band laser, a light-sheet-generating optics, an iodine cell, a frequency monitor unit, and an image acquisition CCD camera. Based on this system, measurements have been carried out on the velocity distributions of a rotating wheel. The results show that the system works well, and the maximum velocity measurement error is less than 2m/s.

INTRODUCTION

In the earlier 1990s, Doppler global velocimetry was developed to realize the measurement of a supersonic or hypersonic flow field [1]. In a Doppler global velocimeter, a molecular/atomic filter is used to convert frequency shifts into intensity variations, Doppler shift of the light scattered from the tracing particles can be measured, and the velocity distribution in the planar flow field illuminated by laser can be determined. Since that the light intensity variation is measured instead of identifying unique particle, the intensity of light scatted by a single tracing particle is not necessary very strong. Therefore, smaller tracing particles than other techniques such as PIV can be used in DGV. DGV can be applied in the measurements of flow fields of a large size wind tunnel and a high speed case. [2-3]

In DGV technique, the frequency shift was obtained by measuring the changes in light intensity pass through the molecular filter. Besides of the Doppler frequency shift caused by the velocity of the particles, many other factors can lead to the changes in light intensity, such as instability in laser light, difference in the characteristics of scattering particle. To resolve this problem, a reference detector is usually used to remove the effects of these error sources. However, the reference detector will bring some new errors, such as, (1) misalignment errors, which occur when pixels of the reference image and the signal image are not mapping the identical area. Large errors can be up to ±2.3m/s if large intensity gradients and low nominal resolution are present [4]; (2) Beam splitting errors, light polarization makes the splitting ratio change. Even with so-called polarization insensitive beam splitter, the splitting ratio is sensitive to light polarization up to ±5% [5].

In 1999, Muller et al [6] presented frequency modulation DGV technique，in which the reference detector is needless and Doppler frequency shift is determined by the ratio of the first and second harmonics of the light intensity modulated signal. Therefore the cost of the DGV system can be reduced significantly and the accuracy of the velocity measurement can be increased [6-9]. In this paper, the working principle of a FM-DGV is described, a FM-DGV system was developed using a CCD camera as the detector. The performance of the system was examined by rotating wheel tests.

PRINCIPLE OF FM-DGV

The basic principle of the DGV is to measure the Doppler shift of the light scattered by moving particles. According to the Doppler shift formula [2]:

$$\Delta f_D = \frac{1}{\lambda}(\hat{o}-\hat{i})\cdot V \qquad (1)$$

where, $\hat{i}$ and $\hat{o}$ are the unit vector of incident and observation light respectively. V is velocity, and λ is the wavelength of light.

A conventional DGV uses a narrow line-width laser to illuminate the measurement plane in the flow field. The scattered light through the molecular filter is received by one camera, terms signal camera. The second camera images the light directly (without filter), terms reference camera. The molecular filter has an absorption line in the frequency tuning range of the laser, thus results a transmission profile with finite length sloping edges (see Fig. 1a). The frequency shifts at each corresponding pixel can be determined by the ratios of intensity values of the reference and signal images, based on the frequency shift function curve (Fig. 1b).

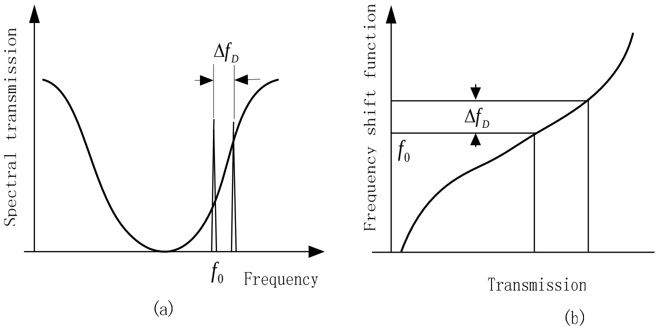

Figure 1 (a) Transmission curve of the molecular filter, (b) curve of the Doppler frequency function

As have described in 'Introduction', the conventional DGV uses two cameras and beam splitter, some errors sources are inevitable, such as beam splitting, image misalignment and noise of the reference camera.

Unlike a conventional DGV, the FM-DGV uses a frequency modulated laser. It's assumed that the laser frequency is sinusoidal modulated as [6]:

$$f_L(t) = f_c + f_h \cos(2\pi f_m t) \qquad (2)$$

with f_c the laser centre frequency, f_h the modulation amplitude and f_m the modulation frequency.

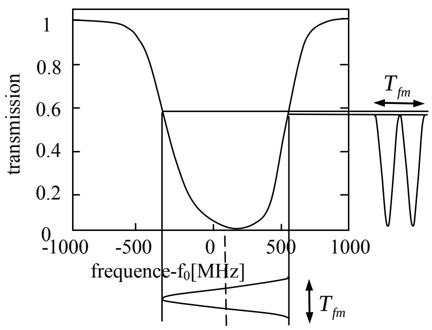

Figure 2 Sketch of the generation of a modulated signal (Ref. [9])

Because of the frequency-intensity conversion of the molecular filter, the camera detects an intensity-modulated signal (Fig. 2). As the transmission curve is nonlinear, the modulated scattered light signal contains several harmonics. Figure 3 shows the typical modulated signal in time domain and its amplitude spectrum (only the first and second order harmonics). The amplitudes of the first and second order harmonics depend on the laser central frequency. In figure 4(a), the first and second order harmonics are plotted with respect to the laser centre frequency. Obviously, a velocity-dependent change in laser frequency caused by the Doppler effect will lead to a change of the first and second order harmonics. As the two amplitude values $A_{1fm}(\Delta f)$ and $A_{2fm}(\Delta f)$ are directly proportional to the scattering light intensity, the division $q(\Delta f) = A_{1fm}(\Delta f) / A_{2fm}(\Delta f)$ is only depended on the laser centre frequency, as shown in figure 4(b). As a result, velocity-dependent Doppler shift can be measured by evaluating the quotient $q(\Delta f)$.[9]

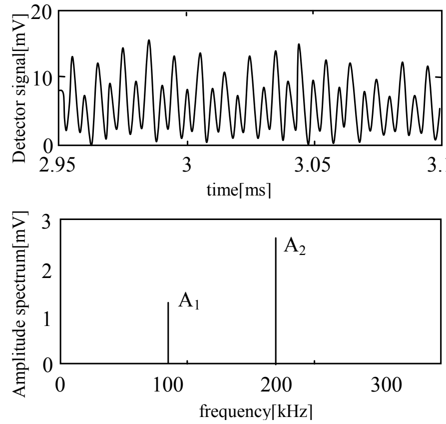

Figure 3 Typical modulated signal in time domain and it amplitude spectrum (Ref. [9])

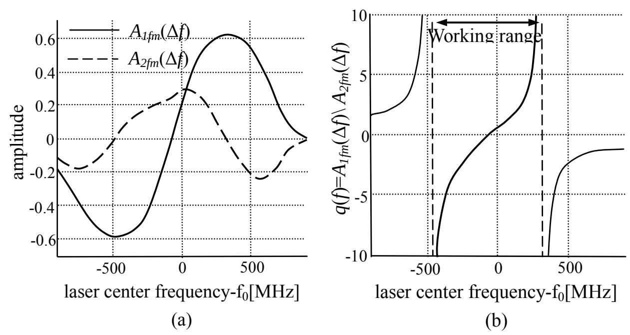

Figure 4 (a) Amplitudes of the first- and second-order harmonics and (b) quotient $q(\Delta f)$ with respect to laser centre frequency

When uses a CCD camera as the detector, a discrete frequency modulation can be achieved based on the frequency shift keying technique. According to the Nyquist criterion, at least three images should be taken in a modulation cycle to evaluate the quotient [7]. The temporal resolution is then given by the image acquisition rate. The purpose of data processing is to evaluate the quotient of the amplitudes of the first and second order harmonics, and the frequency of the Doppler shifted laser light can uniquely be determined referring to the calibrated curve. For a periodic modulation curve, it's enough to just measure the data of one frequency modulation cycle. As shown in figure 5, the curve can be determined by the five points (0)-(4) theoretically. Assuming that the images g(1) and g(3), g(0) and g(4) are the same. Thus, three images per modulation cycle are sufficient to evaluate the quotient. Then the quotient can be calculated by [7]

$$\frac{A_{i,j}(1 f_M)}{A_{i,j}(2 f_M)} = \frac{g_{i,j}(0) - g_{i,j}(2)}{g_{i,j}(0) - g_{i,j}(1) + g_{i,j}(2) - g_{i,j}(1)} \qquad (3)$$

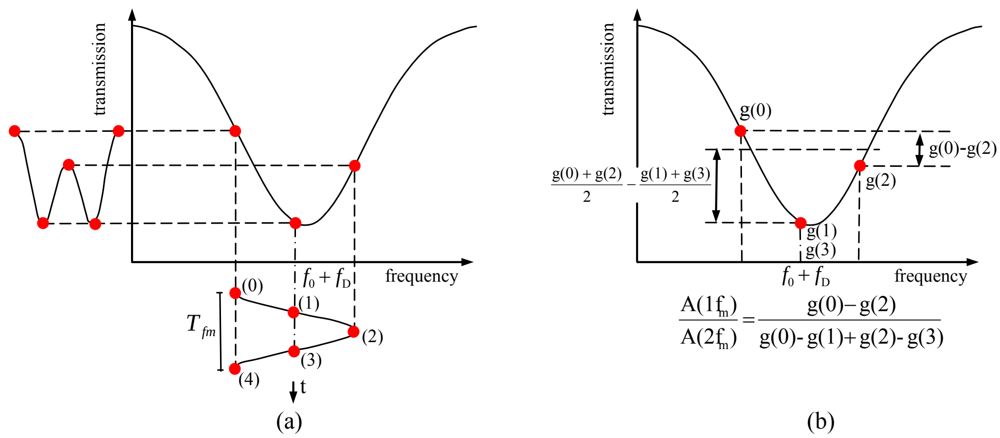

Figure 5 (a) Choose of discrete frequencies in FSK-DGV, (b) the determination of the quotients (Ref. [7])

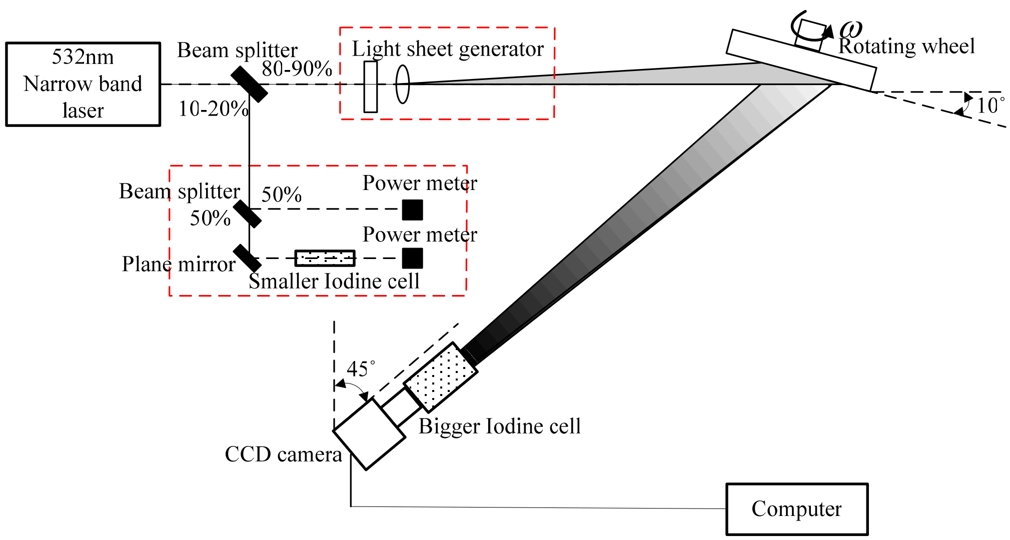

Figure 6 Experimental system

EXPERIMENTAL SYSTEM

The FM-DGV system is schematically shown in figure 6. The system contains a laser, a light sheet generator, a bigger iodine absorption filter, a smaller iodine absorption filter, a CCD camera, auxiliary optical devices and a rotating wheel. Passing through the beam splitter, most part of laser light is used for the velocity measurement, the other part pass through the small iodine molecular filter for light frequency monitoring. The images of scatted light are taken by the CCD camera, and then the images are processed in a computer.

Laser

For the DGV technique, the laser line-width and frequency stability are the two important parameters of the laser. In this system, SLM532-50 semiconductor laser is used. It can generate a continuous laser light at the wavelength of 532 nm. The light width is less than 1MHz, and the maximum output energy is 50mw. Although the laser power is low, it’s enough for the purpose to realize the function of a FM-DGV system. The laser frequency can be tuned by adjusting the crystal temperature in it. The minimum adjustment step is 30MHz corresponding to a temperature interval of 0.01K, and the range of frequency tuning is about 30GHz. The laser beam was converted to a laser sheet with thickness of about 1mm at the light waist by the auxiliary optical devices.

Iodine molecular filter

Iodine molecular filter, which also called "Iodine cell" or "absorption cell", is a cylinder filled with iodine vapour made of quartz glass. There is a glass barrel with optical windows on each end. The bigger filter is of 75 mm in diameter and 150 mm in length, and the smaller one is of 25 mm in diameter and 120 mm in length. The cylindrical portion of the cell are wrapped with strip heaters and heat insulation tape, and maintained at an elevated temperature 340-380K, At this point, no iodine crystals are present in the cell barrel. The temperature control precision here is 0.1K. The side-arm, which is connected to the body of the cell, is maintained at a lower temperature 310-325 K, and the TEC technique was applied to control the temperature. As the transmission profile is dependent on the side-arm temperature, the temperature control precision is 0.01K.

CCD camera

A BM-141GE camera was used, which is a digital monochrome progressive camera produced by JAI Ltd.. Its S/N ratio is better than 58 dB, and the active pixels is 1392×1040. It can output 12, 10 or 8-bit images. 8-bit image mode has been taken this paper.

EXPERIMENTAL RESULTS AND ANALYSIS

Calibration of the system

A rotating wheel of 20cm in diameter is used to supply a velocity field. Its speed is from 0 to 3500 rpm. Because of the low laser power, the measurement region can't be too large. As shown in Figure 6, the angle between incident light and the wheel surface is 10°, results in an illuminating strip of about 10mm in width. The rectangular region illustrated in figure 7 is the measuring zone. The distance R0 between the rectangle bottom and the wheel's centre is 3.5 cm.

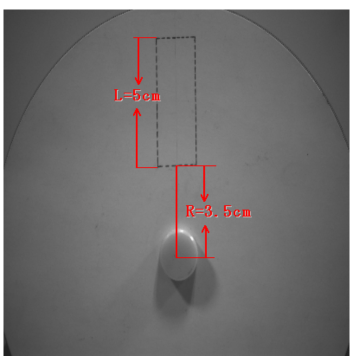

Figure 7 Measuring zone on the rotating wheel

Refer to Figure 5, during calibration, groups of three frequency points must be chosen. In each group, frequency intervals between the both side points to the centre frequency are the same, 180MHz. The three frequency points must be in the absorption well. The original centre frequency was chosen at 0, and it varies from -120~120MHz with a scanning step of 30MHz during calibrating. According to the formula (3), the calibration curve of the relationship between the centre frequency and quotient of the first and the second harmonics will easily obtained. It's noted that intensity values have been calculated by processing the mean values of 5×5 pixels in the measuring zone. Figure 8 shows the calibration curve, for which 3 orders polynomial has been applied to fitting the curve, and the results look reasonable.

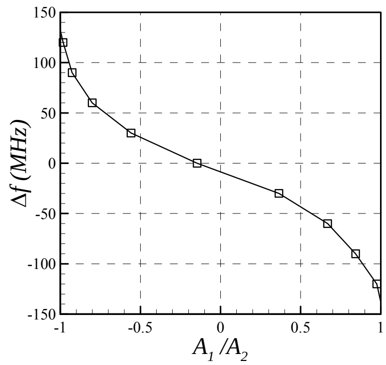

Figure 8 Calibration curve of the relationship between the centre frequency difference and quotient of the first and the second harmonics

Velocity measurement on the rotating wheel

Based on the formula (1), the measured velocity component is:

$$V_D = \Delta f_D \frac{\lambda}{2\sin(\theta/2)} \tag{4}$$

where, θ is the included angle between the incident light direction and the observation direction.

The measured tangential velocity is calculated as $V = V_D / \cos\phi$, where ϕ is the included angle between the measured velocity component and the tangential direction of the wheel.

Figure 9 shows the test results of the tangential velocity distribution along radius direction. The velocity values are the averaging results of 10 pixels on the same radius. The true values of velocity calculated by the rotating speed n and the radius r were also presented in Figure 9 for the purpose of comparison. Figure 9 presents the velocity distributions for the cases of n=2500rpm and 3500rpm, respectively. It's shown that the maximum absolute errors are 1.43 m/s and 1.76 m/s for the two rotating speeds, less than 2 m/s, while the maximum relative error is 8.4%. Since that the velocity magnitude in this study is relative small, the relative error shows a large value. The values of absolute error are acceptable for DGV measurements, considering that this technique is developed mainly for the high speed cases, and the absolute error will not increased with the increase of measured velocity.

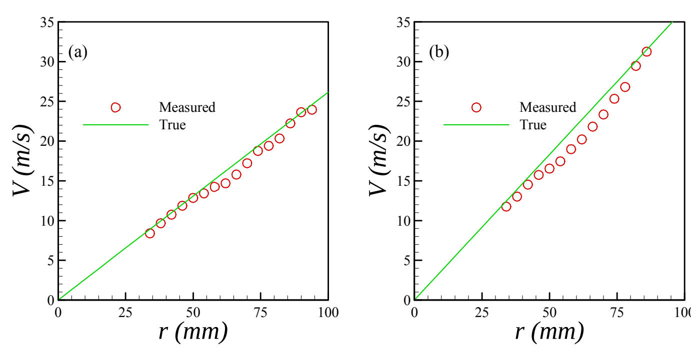

Figure 9 Tangential velocity distribution with a radius, (a) n=2500rpm, (b) n=3500rpm

In addition, the measured tangential velocity distribution presented in figure 9 is not linear. It's observed that the measured values are in good agreement with the true values at the small and large radius, while data at the middle region is poor. Two reasons should be considered for the poor results at the middle radius. One reason is that the calibration curve is an averaging data of a small area near the middle results, but not for each pixel, which leads to the error values showing different values at different radius. The second reason is that the original value of basis point frequency (i.e. the centre frequency at zero speed) is different with that for calibration.

CONCLUSIONS

FM-DGV technique was introduced in this paper. A FM-DGV experimental system has been developed of which a CCD camera being as the signal detector. Preliminary tests were carried out to examine the performance of the system. The results show that the developed FM-DGV system can work properly, and the velocity measurement error is less than 2m/s. In order to reduce the measurement error, the measurement method needs to be improved further.

ACKNOWLEDGEMENT

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