A novel Laser Doppler Velocimeter based on a liquid lens

Chongbin Xia, Jian Zhou*, Xiaoming Nie, Rong Huang
College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha, China

*Corresponding author: wttzhoujian@163.com

Abstract—This paper proposed a novel Laser Doppler Velocimeter (LDV) based on an electrically tunable lens (ETL) to change the working distance and to extend the measuring range of LDV. On the basis of Gaussian optics, the positions along with the size of waist spot are simulated under different driving current of ETL. In addition, the working distance and measuring range of LDV under different offset lenses were measured. The results demonstrate that the LDV based on ETL is able to change the working distance and effectively enlarge the measuring range of LDV, whose volume is reduced simultaneously.

1. Introduction
Laser Doppler Velocimeter (LDV) obtains the moving velocity of carriers via gauging the interference signal mixed the reference together with the signal light. As a novel speed sensor, LDV possesses the advantages of non-contact measurement, no interference with the target, and high speed measurement accuracy. In 1964, Yeh and Cummins confirmed that the velocity of a fluid could be obtained via utilizing the technique of laser Doppler frequency shift[1]. Subsequently, the structure of LDV, mainly including the dual-beam differential type and the reference-beam type, has been altered based on different application scenarios to measure the motion velocity, displacement, vibration and length[2]. However, it has been found that LDV can only scale the speed within a certain range.

The dual-beam differential type requires that the moving surface is always located in the control body (the area where two beams intersect). Once the object leaves the control body, the Doppler signal is lost. In order to solve this problem, Jian Zhou put forward the multi-point layer-type LDV by using multiple probes so that the measuring range of the system equals to the sum of the measuring range of a single probe[3] and Doppler signal is processed with the technique of tracking filter and digital autocorrelation. The multi-point stratification scheme can solve the problem that dual-beam LDV can not measure the velocity while out of focus. However, the system structure is more complex and the signal processing is harder in the later stage.

The reference-beam LDV can be used for defocusing measurement, but it is purely able to determine the movement speed within a certain distance from the position of the waist spot, which is associated with the position as well as the size of the waist spot. Once the moving object departs from the effective area, the Doppler signal is lost. Aiming at adjusting the working distance of the reference-beam LDV, a beam transformation scheme is adopted, as shown in Fig. 1, where two lenses with fixed focal length of $F_1$, $F_2$ are used. $d$ is the distance between two lenses, $L_0$ is the working distance of the system, and $\Delta L = \Delta L_1 + \Delta L_2$ is the measuring depth of filed. $(L_0 - \Delta L_1) \sim (L_0 + \Delta L_2)$ is the measuring range of the system.
Although this method can change the working distance, the measuring range of this system is still limited. On the other hand, due to the small measurement depth of field with a considerable volume, the speedometer has a small degree of freedom of installation and has certain requirements on the installation environment, which generally fails to satisfy the demand of practical applications. In order to expand the scope of the system, it is necessary to change the distance between two lenses or to reform the lens combination. But transforming the lens distance through mechanical structure will extend the volume along with the complexity of system, which restricts the operating range of the speedometer to a great extent. Nevertheless, it is impossible to alter the lens combination at any time in practical engineering applications. At present, there is no other reasonable method to realize the expansion of measuring range.

On the basis of the working principle of the vertebrate eye lens, researchers have invented an adjustable liquid lens[4]. Its shape can be changed by driving current through the principles of electro wetting effect, mechanical pressure, etc., resulting in the change of the focal length. At present the mature product is called electrically tunable lens (ETL). Introducing differences in liquid lens radius of several micrometers is capable to produce the identical optical effect as shifting the entire lens on a scale of centimeter. Thus, the optical system can be more compact with fewer lenses as well as less or no translational movement. The liquid lens has been utilized in the fields of microscope, laser radar,[5, 6] etc., due to the advantages of straightforward structure, lower power consumption as well as the sharp response time of systems (in order of milliseconds).

In this paper, a novel structure of LDV with an ETL was proposed to adjust the working distance of LDV without motive mechanical part. Firstly, the feasibility of employing a liquid lens to transform the Gaussian beam emitted by the LDV was theoretically analyzed. Afterwards, a LDV on the basis of the ETL was constructed in order to change the position of the waist spot via changing driving current without increasing the displacement mechanism. The new structure greatly increased the measuring range of LDV to meet the requirements of different measurement distances. And the volume of the speed measurement system is reduced.

2. Theory

2.1. Relationship between quality factor and working distance

On account of the complicated characteristics of the scattering surface, the signal-to-noise ratio of the Doppler signal will be reduced, causing signal loss named signal shedding. At this time, the scattered light does not contain Doppler frequency information and the results obtained by any algorithm are meaningless[7]. The paper employs the quality factor[8] $Q$ as the foundation for evaluating the quality of Doppler signal, which is defined as the ratio of the peak spectrum in the signal spectrum to the root mean square of all other points, as shown in (1).
In order to realize the validity of Doppler signal, the threshold value of quality factor $Q_0$ is firstly specified in the experimental process. If the quality factor of Doppler signal $Q$ is below the threshold value $Q_0$, the signal is considered to be invalid, otherwise, the signal is judged to be effective.

The relationship between laser Doppler signal intensity $I$ and optical path structure parameters is [9]:

$$I = \sqrt{E[i^2(t)]} = \frac{akq}{2} \frac{D}{2w} \sqrt{\frac{\pi k_2}{2k}}$$

where $q$ is the average light intensity on the observation surface, $a$ is a constant related to the reference light intensity, $E[i^2(t)]$ is the mean square value of the output current of the photodetector, $k$, $k_1$, $k_2$ are constants, $2\omega$ is the spot diameter on the scattering surface (assuming it is circular), and $D$ is the diameter of the photosensitive surface of the photodetector.

As derived from (2), the intensity of Doppler signal will be enhanced by shrinking the diameter of the spot. According to the properties of the Fourier transform, with an escalating $I$, the spectrum peak value of Doppler signal $P_k$ will increase, while $P_i(i\neq k)$ is principally the spectrum value of noise independent of the signal light intensity. Therefore, the increment of $P_i(i\neq k)$ is less than $P_k$. As derived from (1), the value of quality factor will simultaneously ascend. So quality factor is inversely proportional to the size of spot. Consequently, as the measurement point is approaching the waist spot in Fig. 2, $Q$ performs an upward trend. Nevertheless, when the measurement point is deviating from the waist spot, the Doppler signal strength is weakened due to the excessive light spot, causing the escalation of $Q$. On account of the symmetry of the Gaussian beam, the quality factor $Q$ is smaller than the threshold $Q_0$ beyond a certain range on both sides of the waist spot. As shown in Fig. 2, the Doppler signal is effective only when the measured point is within $L_1$~$L_2$, which is the measuring range of LDV.

2.2 Principle of Gaussian beam transformation based on ETL

This paper designs LDV based on ETL, which adopts ETL and fixed focal length lens $F_2$ to form the scheme of beam transformation system, as shown in Fig. 3. $\omega_0$ is the waist spot radius of the incident Gaussian beam; $\omega_2$ is the waist spot radius of the outgoing Gaussian beam after passing the duplet lenses system; $l_1$ is the separation of the incident Gaussian beam waist spot from ETL; $d$ is the distance between ETL and fixed focal length lens; $l_2$ is the length between the waist spot of the output Gaussian beam and fixed focal length lens. Consequently, the working distance and measuring range of LDV is primarily conditional on $l_2$, $\omega_2$. 

Figure 2. The distribution of $Q$
The core component of ETL is a container which is filled with optical fluid as well as sealed off by an elastic polymer membrane[10], the liquid shape is changed by controlling the driving current to change the liquid pressure, and finally the focal length of the liquid lens is changed, as illustrated in Fig. 4(a). The relationship between the focal power of the ETL (Unit: diopter, Dpt) and the driving current is:

\[ D_{\text{pt}} = \frac{1}{F_{\text{ETL}}} = 0.022i_{\text{ETL}} + 4.9276 \]  \( (3) \)

where \( i_{\text{ETL}} \) is the driving current of ETL, \( F_{\text{ETL}} \) is the focal length of ETL without offset lens.

When the focal power range of ETL cannot meet the requirements, the range is variable with an additional offset lens, as interpreted in Fig. 4(b). Acknowledged by (4), the focal length range is able to be theoretically shifted to any desired value.

As shown in Fig. 5, the focal power of the ETL can be changed from only positive to positive or negative by adding an offset lens.

\[ \frac{1}{F_{\text{ETL-offset}}} = \frac{1}{F_{\text{ETL}}} + \frac{1}{F_{\text{offset}}} + d_{\text{ETL-offset}} \left( F_{\text{ETL}} \cdot F_{\text{offset}} \right) \]  \( (4) \)

where \( F_{\text{ETL-offset}} \) is the focal length of ETL with offset lens, \( F_{\text{offset}} \) is the focal length of offset lens, and \( d_{\text{ETL-offset}} \) is the distance between offset lens and ETL.

The output beam of LDV is still Gaussian beam after travelling through the lenses. The transformation matrix from the waist spot of the incident Gaussian beam to the surface just after fixed focal length lens (see Fig. 3) is[11]:

\[ T = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 & d \\ -1/F_{2} & 1 & 0 & 1 \\ -1/F_{\text{ETL-offset}} & 1 & 0 & 1 \end{bmatrix} \]  \( (5) \)
Considering the propagation of the Gaussian beam through an optical system (as depicted in Fig. 3), the complex beam parameters of the waist spot position of the incident Gaussian beam $q_0$, together with the complex beam parameters of the surface just after $F_2$, $q_F$, are associated by:

$$q_F = \frac{Aq_0 + B}{Cq_0 + D}$$  \hspace{1cm} (6)

$$q_F = q_2 - l_2 = i \frac{\pi \omega_2^2}{\lambda} - l_2$$  \hspace{1cm} (7)

where $q_0$ is characterized as $q_0 = (i \pi \omega_0^2) / \lambda$, $\lambda$ is the wavelength of laser beam, $q_2$ is the complex beam parameter of the waist spot position of the outgoing Gaussian beam. Via equating the real and imaginary parts of (6) and (7), respectively, the waist spot position $l_2$ as well as the size of waist spot $\omega_2$ is able to be calculated by (8) and (9). Where $A$, $B$, $C$, $D$, $M$, $N$ are constants associated with the incident Gaussian beam.

$$\omega_2 = \sqrt{\left\{B - \frac{C}{F_{\text{ETL-offset}}}\right\}d + 5896i/ \left[1 + \frac{(d - M)(1)BC}{F_{\text{ETL-offset}}}i - \frac{d}{F_2} - D\right]}$$  \hspace{1cm} (8)

$$l_2 = \text{real}\left[\left(d - \frac{M}{F_{\text{ETL-offset}}}i + M\right) / \left(1 + \frac{M(d - 1)}{F_{\text{ETL-offset}}}i - \frac{d}{F_2} - Ni\right)\right]$$  \hspace{1cm} (9)

When parameters $\omega_0$, $l_1$, $d$, $F_2$ are determined, the focal length of ETL $F_{\text{ETL-offset}}$ can be changed by changing the driving current, so that the waist spot position and the waist spot radius of the outgoing Gaussian beam change with the driving current, and finally change the working distance of the LDV, enlarge the measuring range of LDV.

3. Simulation and experiment

3.1. Simulation analysis

According to the analysis in section 2, the optional variables in the system are $l_1$, $d$, $l_2$, $\omega_2$ and the focal length range of ETL. In order to analyze the effect of different lens spacing $d$ and different focal length of offset lenses $F_{\text{ETL}}$ on the working distance of LDV, the relationship between lens spacing and the location along with the size of waist spot, as well as the relationship between lens focal length $F_{\text{offset}}$ and the location along with the size of waist spot were analyzed by simulation. Assume that $l_1 = 0$ which means that the ETL is located at the waist spot of the incident Gaussian beam. When the focal length of offset lens $F_{\text{offset}}$ is selected, the variation range of $F_{\text{ETL-offset}}$ is determined, and the relationship between driving current and the position along with the size of the waist spot under different lens spacing are shown in Fig. 6. As observed from Fig. 6, under the same driving current, reducing the lens pitch can increase the position of the waist spot, which means the working distance of the LDV can be increased, but the radius of the waist spot also increases at this time, which will cause the Doppler signal strength to decrease.

The variation range of $F_{\text{ETL-offset}}$ depends on the selection of the offset lens. When the requirement of the working distance is given, in order to meet the requirements of the aperture of the offset lens, three
varieties of offset lenses with different focal lengths are selected to reform $f_2$ along with $\omega_2$, whose focal lengths are -19mm, -25.4mm, -50.8mm, respectively. The relationship between waist spot position and driving current, waist spot radius and driving current with different offset lenses are simulated.

As observed from Fig. 7: With the same offset lens, as the driving current increases, the position of the waist spot gradually decreases, that is, the working distance of the speed measuring system gradually decreases. As the focal length of the offset lens gradually decreases, the variable range of the position of the waist spot progressively escalates. However, as the focal lengths of the offset lens decreases, the variation region of the waist spot radius gradually increase, which will result in a decline in the Doppler signal strength.

Figure 6. Relationship between driving current and the position along with size of waist spot under different $d$: (a) Relationship between the position of waist spot and driving current; (b) Relationship between the size of waist spot and driving current

Figure 7. Relationship between position along with size of waist spot and driving current under different offset lenses: (a) Relationship between the position of waist spot and driving current; (b) Relationship between the size of waist spot and driving current

Therefore, when selecting the distance $d$ between lenses and the focal length of offset lens $F_{\text{offset}}$, it is necessary to meet the requirements of the system working distance, ensure the validity of the Doppler signal in the entire working distance range, and at the same time avoid the excessive size of the system.

3.2. Experiment results and discussion

In order to further verify the improvement of the measuring range of LDV by ETL, the threshold value of quality factor $Q_0$ is firstly specified in the experimental process, the turntable with fixed angular speed is employed as the velocity source, as shown in Fig. 8, where $L$ is the range from the measuring point to fixed focal length lens. By measuring the quality factor $Q$ of different distances, the working distance and measuring range of the LDV under different offset lenses and different driving currents are measured.

As shown in Fig. 9, the distribution of waist spot under different driving currents with different offset lenses obtained by the experiment is basically consistent with the simulating results in Fig. 6.
As analyzed in section 2, the Doppler signal is only valid within a certain range neighboring the waist spot, in other words, LDV has a maximum as well as a minimum measurement distance, whose interval is the measuring range of the LDV. The distribution of the measurable range of LDV with different offset lenses and different driving currents is shown in Fig. 10. The same color region in the Fig. 10 is the measurable range of the corresponding offset lens. The relevant measurement parameters are shown in table 1.

| $F_{offset}$ (mm) | d (mm) | $L_{min}$ (mm) | $L_{max}$ (mm) | $\Delta L$ (mm) |
|-------------------|-------|----------------|----------------|-----------------|
| -50.8             | 85    | 300            | 1900           | 60 $\leq \Delta L \leq 130$ |
| -25.4             | 125   | 700            | 3300           | 70 $\leq \Delta L \leq 120$ |
| -19               | 134   | 1120           | 3200           | 60 $\leq \Delta L \leq 110$ |
In Table 1, $\Delta L$ is the measurement depth of field, $L_{\text{max}}$ and $L_{\text{min}}$ are the maximum and minimum measuring distances of the LDV within the whole driving current range, respectively. Thus, the measuring range of LDV is $L_{\text{min}} \sim L_{\text{max}}$. As can be seen from Fig. 10 and Table 1, when $F_{\text{offset}}=-50.8\text{mm}$, the variation range of the position of waist spot is the largest with a smallest $d$, which is beneficial to diminish the volume of the system. However, as interpreted in Fig. 7, when the driving current is less than 30 mA, the waist spot radius is too large, causing the weakened scattered light which generates an invalid Doppler signal. Therefore, when the position of the waist spot is above 1900 mm, the quality factor of LDV is below the threshold. Meanwhile the Doppler signal cannot satisfy the measurement requirements (as shown in the blue area in Fig. 10). When $F_{\text{offset}}=-19\text{mm}$, an effective Doppler signal is able to be obtained in all variations of the Gaussian beam waist spot. Nonetheless, the variation range of the Gaussian beam waist spot attains the minimum with a maximum $d$, which will result in an oversized speed measuring system. Combined with the above analysis, when the offset lens with $F_{\text{offset}}=-25.4\text{mm}$ is selected, not only the working distance of LDV can be changed, ensuring the effectiveness of the Doppler signal in the whole working range with an extended measuring range of existing LDV, but also the measurement depth of field can be gradually increased as the driving current decreases (see Fig.10), enhancing the adaptability of the LDV to the roughness of the moving surface. Moreover, the interval between lenses is shrunk to a certain extent with the purpose of compressing the volume of the velocity measurement system.

4. Conclusion

In order to change the working distance and increase the measuring range of LDV, this paper proposes a novel LDV scheme based on ETL. The results show that this LDV based on ETL can make the Gaussian beam waist spot position move and change the working distance of the LDV simply by controlling the driving current without increasing the displacement mechanism, which greatly improves the measuring range of LDV and is of great significance to the engineering application of LDV.

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