Precise force measurement method by a Y-shaped cavity dual-frequency laser

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A novel precise force measurement based on a Y-shaped cavity dual-frequency laser is proposed. The principle of force measurement with this method is analyzed, and the analytic relation expression between the input force and the change in the output beat frequency is derived. Experiments using a 632.8-nm Y-shaped cavity He-Ne dual-frequency laser are then performed; they demonstrate that the force measurement is proportional to a high degree over almost five decades of input signal range. The maximum scale factor is observed as $5.02 \times 10^5$ Hz/N, with beat frequency instability equivalent resolution of $10^{-5}$ N. By optimizing the optical and geometrical parameters of the laser sensor, a force measurement resolution of $10^{-6}$ N could be expected.

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Precise measurement of force and force-related magnitudes, such as acceleration, pressure, and mass, is an often demanded task in modern engineering and science. In recent decades, some research efforts have been intensified to utilize optical measurement procedures for obtaining precise force measurement.

In most previous attempts to apply the optical effect for force measurement, the intensity, polarization state, or phase of the transmitted light was often modulated by the input force. They are commonly called “passive optical force sensor”, examples of which are the optical fiber micro electro mechanical system (MEMS) force sensors and the optical fiber Bragg grating force sensor. The optical fiber elastic deformation effect in interferometers was also used to carry out force measurement by modulating the phase of the transmitted light. In addition, the silicon-on-insulator MEMS (SOI-MEMS) technology used in force sensors is now being widely studied. However, these methods and technology always result in nonlinear characteristics, which is important to the precious measurement.

Compared with the passive optical force sensor, active optical force sensor, another optical measurement technique is more promising. This technique enables the modulation of the laser frequency to be strictly proportional to the input force, which has been a persisting issue for decades now.

One type of active optical force sensor that has been widely researched about is the one that utilizes the laser crystal’s photoelastic effect, such as Nd:YAG. In 1989, Holzapfel et al. carried out a force-to-frequency conversion using the photoelastic effect inside a He-Ne laser cavity. They demonstrated that precise conversion of force to frequency can be achieved by applying the resonator-internal photoelastic effect. In 1993, they developed the force measurement based on the photoelastic effect in solid-state lasers. In 2000, utilizing the same principle, they achieved a very large measurement range of nine decades and a strictly proportional conversion of force into frequency for modulating frequencies starting from DC up to at least 100 kHz. Meanwhile, Zhang et al. realized the determination of internal stress in Nd:YAG crystal by applying the laser frequency splitting method with high resolution of 5 Pa. Its resolution is approximately five to eight orders of magnitude higher than those of conventional methods. They also used an all-optical pressure sensor and achieved a sensitivity of 1.31 MHz/kPa.

In this letter, another active optical force sensor based on the press-refractivity effect of gas is presented. The key basis of this sensor is a Y-shaped cavity dual-frequency laser. The laser’s basic principle and structure, as well as the force sensor’s basic principle, signal transforming procedures, and mathematical modeling are described. The primary experimental study and its setup are reported. The experimental results are discussed and analyzed.

The main design features of the force sensor in this study are shown in Fig. 1. Force-to-frequency conversion is carried out by means of a Y-shaped cavity dual-frequency laser (Fig. 2) and a gas syphon of special structure.

For convenience, we specify two terms used in this letter. P-light means that the electric field vector is perpendicular to the plane of incidence, while S-light means that the electric field vector is parallel to the plane of
incidence. A Y-shaped cavity dual-frequency laser is a novel dual-frequency laser based on the Y-shaped cavity frequency splitting method. The laser amplifier, in which both the S-light and P-light pass through, provides gain for them. The portion of the cavity formed with mirror 1 and the polarization beam splitter (PBS) is called the “common cavity”. The S-light and the P-light are separated from each other by the PBS and then pass through the different sub-cavities. M1 is the output plane mirror with reflectance of 99.7%. Meanwhile, M2 and M3 are highly reflective spherical mirrors with reflectance of 99.9% and curvature radius of 2 m. The sub-cavity formed with the PBS and M2 is called “S sub-cavity”, while that formed with the PBS and M3 is called “P sub-cavity”. The common cavity joined with the S sub-cavity and the P sub-cavity is called the “Y-shaped cavity” in view of its shape. W is an anti-reflective window, which is a crystal glass substrate coated by anti-reflective film.

The key element of the Y-shaped cavity dual-frequency laser is the PBS, whose reflectance for S-light and transmittance for P-light are both 99.9% at the specific angle of incidence due to its specially designed film structure and deposition process of optical coatings. In such case, the laser oscillator is excited in two longitudinal modes, which are polarized linearly and orthogonally to each other. According to the principle of laser, the frequencies for S-light $\nu_s$ and P-light $\nu_p$ can respectively be written as

$$\nu_s = s \cdot \frac{c}{2(l_c + l_t)}; \quad \nu_p = p \cdot \frac{c}{2(l_c + l_p)},$$

(1)

where $l_c$ is the optical length of the common cavity; $l_p$ is the optical length of the P sub-cavity; $l_t$ is the optical length of the S sub-cavity; and $s$ and $p$ are natural numbers.

As shown in Fig. 3, the gas sylphon is composed of the quartz film, glass ceramic plate, and sensitive gas. The super-thin quartz film is conglutinated with the glass ceramic plate to form an airtight room, which is filled with sensitive gas such as air of a certain pressure. There is a cover plate on the gas sylphon in order to minimize the influence of environmental factors, including temperature and environmental pressure. The venthole of the gas sylphon is connected to the sensitive gas tube in the P sub-cavity of the laser (Fig. 2).

When $F$ is applied on the center of the quartz film along the sensitive axis as shown in Fig. 1, it will induce a change in the sensitive gas’ refractive index $\Delta n$, given by

$$\Delta n = \frac{5}{128} \frac{k \rho R^4}{V_0 D (1 + \eta)} \cdot F,$$

(2)

where $k$ and $\rho$ are the sensitive gas’ Gladstone-Dale constant and density, respectively; $D$ is the quartz film’s bending rigidity; $R$ is the glass ceramic plate’s radius; $V_0$ is the sensitive gas’ initial total volume including the cubages of the gas sylphon and sensitive gas tube, depending on the glass ceramic plate’s radius $R$ and the nominal scale factor $E$ is constant in relation to the parameters of the laser and gas sylphon.

The experimental scheme as shown in Fig. 4 was used to investigate the principle properties of the new force measurement technique. The experimental setup is composed of three units.

(i) A force transducer – it included a Y-shaped cavity
when the sample time was 50
and the end of each stress interval can be explained by
sionally observed beat frequency peaks at the beginning
test and analysis are on the horizon. In Fig. 5, the occa-
the other parameters of the experimental setup
were the same as that of a quartz film: \( t = 0.1 \) mm; glass
ceramic plate: \( \varepsilon = 0.5 \) mm; and sensitive gas: air with 1
standard atmosphere pressure.

(ii) A selecting and controlling system of operating
point – it included two avalanche photo diodes (APDs),
two piezoelectric transducers (PZT), an amplifier and fil-
ter (A&F), a PZT power supply (PS), a data acquisition
circuit (DAQ), and a computer (PC).

(iii) A beat frequency acquisition system – it included
an APD, a frequency counter (FC, Agilent 53131A), and
a PC.

Precisely defined input signals were produced with
different calibrated test masses \( m_i \). With constant ac-
celeration due to earth gravity \( g \approx 9.8 \) m·s\(^{-2}\), the
different forces \( F_i = m_i g \) acting on the quartz film of the
gas sylphon were produced. The beams emerging from
M2 and M3 provided the operating point (i.e., the longi-
dudinal modes’ relative position in the free spectral range
of laser) selecting and controlling channel. Their intensi-
ties were transformed into electrical signal by APD 1 and
APD 2, and then amplified and converted from analog
signals into digital signals by A&F and DAQ. A simple
but effective method of operating point controlling, based
on a comparison of two mode intensities, was applied to
keep the laser operating stably through the PZT \( \delta \)
and PS. Using this method, the center of the two longitudi-
nal modes was selected and controlled at the center
frequency of the laser transition. Radiation, emerging
from M1, passed through a polarizer and was detected
by APD 3. The force-dependent change in the beat fre-
frequency \( \Delta v \) between the S-light and the P-light \( \delta(\Delta v) \)
was then measured by means of the frequency counter
(Agilent 53131A). All the measurement processes above
were controlled and harmonized mostly by the software
in the computer.

The dependence of the beat frequency \( \Delta v \) on the
input signal \( F \) was investigated experimentally for the gas
geometry parameters. A slight sylphons of different in-
crease in the beat frequency \( \Delta v \) was observed for the
sudden changes in input signal caused by placing the
mass on the quartz film of the gas sylphon. After the
removal of the mass, the beat frequency dropped back to
its previous value. A series of frequency rises and drops
of the same magnitude occurred when the same mass of
984 mg was put and removed as shown in Fig. 5, indicat-
ing that this reaction is reproducible. From the constant
parts of the measured time, it is concluded that this test
process was in operation with good static character-
istic. The maximal rise time of about 100 \( \mu \)s was observed
when the sample time was 50 \( \mu \)s; hence, we conclude that
the dynamic bandwidth of our measurement setup is of
the order of kilohertz. Further dynamic characteristic
test and analysis are on the horizon. In Fig. 5, the oc-
casionally observed beat frequency peaks at the beginning
and the end of each stress interval can be explained by

Fig. 5. Time trace of the beat frequency caused by a series of
input step masses, mass step \( m = 983.8 \) mg, and equivalent
force \( F = 0.0096 \) N; geometry parameters of the quartz film
and glass ceramic plate: \( \gamma = 20 \) mm, \( t = 0.1 \) mm, and \( \varepsilon = 0.5 \)
mm setup.

the necessary manipulation of taking the mass on and
off.

From a sequence of the above-described load test with
different test masses, the change in the beat frequency at
the well-known constant earth gravity \( g \) was ascertained
as a function of the test mass weight. The increase in
the experimental sensitivity (i.e., scale factor) had been
realized in accordance with Eq. (3) by changing the
diameter of the gas sylphon. The static characteristics
for the three measurement experiments with scale fac-
tors \( E_1 = 2.24 \times 10^9 \) Hz/N, \( E_2 = 3.12 \times 10^9 \) Hz/N, and \( E_3 =
5.02 \times 10^9 \) Hz/N are shown in Fig. 6, with the values of
the three scale factors obtained from the experimental
data. The diameters of the gas sylphons cor-
responding to the three different scale factors (i.e., \( E_1, E_2, \) and
\( E_3 \) were 25, 30, and 40 mm, respectively. According
to Eq. (3), the nominal scale factors were calculated as
\( \tilde{E}_1 = 2.25 \times 10^9 \) Hz/N, \( \tilde{E}_2 = 3.15 \times 10^9 \) Hz/N, and \( \tilde{E}_3 =
5.06 \times 10^9 \) Hz/N. They were mostly in good agree-
ment with the experimental value when taking the manip-
ulation error in to account. The relationship formula
between the changes in the beat frequency \( \Delta v \) and the
applied force \( F \) can respectively be written as \( \delta(\Delta v) =
(2.24 \times 10^9 F - 1.68 \times 10^9) \) Hz/N, \( \delta(\Delta v) =
(3.12 \times 10^9 F - 1.32 \times 10^9) \) Hz/N, and \( \delta(\Delta v) =
(5.01 \times 10^9 F - 4.63 \times 10^9) \) Hz/N through data fitting. The fitting residual errors

Fig. 6. Static characteristics of the laser force transducer.
Different scale factors \( E_1, E_2, \) and \( E_3 \) are obtained by chang-
ing the diameter of the gas sylphon: \( \star: E_1 = 2.24 \times 10^9 \) Hz/N,
\( R_1 = 25 \) mm; \( \Delta: E_2 = 3.12 \times 10^9 \) Hz/N, \( R_2 = 30 \) mm; \( \triangledown: E_3 =
5.02 \times 10^9 \) Hz/N, \( R_3 = 40 \) mm; \( + \) is the stability of the beat
frequency in a short time (about 10 minutes).
were $\delta a_1 = 1.67 \times 10^3$ Hz, $\delta a_2 = 2.55 \times 10^3$ Hz, and
$\delta a_3 = 3.60 \times 10^3$ Hz, respectively. The fitting curves and
the experimental data points in Fig. 6 indicate that the
system has a good linearity. All the experimental
results were taken after having reached the thermal sta-
ility of the laser transducer.
A novel force measurement system covering an input
range of five decades with a resolution of $10^{-5}$ N has
been demonstrated based on a Y-shaped cavity dual-
frequency laser.

The upper measurement limit of the input force is de-
termined by the laser’s lasing bandwidth and the scale
factor. The low measurement limit is only determined
by the resolution, depending on the scale factor and
the stability of the beat frequency $\Delta \nu$. In our exper-
iment, the highest scale factor is $E_3=5.02\times10^9$ Hz/N
and the longitudinal mode spacing is about 900 MHz,
with the upper measurement limit recorded at approxi-
ately $F_{\text{max}}=0.18$ N. During the experiment, the ob-
served short-time (about 10 minutes) beat frequency in-
stability was 100 kHz; therefore, the resolution is about
$10^{-5}$ N.

The increase in scale factor can be achieved easily by
enlarging the diameter of the gas sylphon or by using
the sensitive gas high-refractive index. However, for
the constant lasing bandwidth, the upper measurement limit
will decrease with the increase in the scale factor. In
all, it only enhances the stability of the beat frequency,
which ensures good performances of the resolution and
the upper and low measurement limits.

The preliminary performance of the upper and low
measurement limits still has its flaws due to the beat
frequency instability of the laser. The main disturbance
of the beat frequency comes from the variation of the
difference of the two sub-cavities’ length due to ther-
mal expansion. In the laser, the substrate of the PBS
is made of crystal glass, whose expansion coefficient is
$2\times10^{-7}$ /°C. This will lead to the P sub-cavity length’s
thermal change of $4\times10^{-10}$ m/°C, which is equivalent to
1.25$\times10^6$ Hz/°C. In our experiment, the observed short-
time beat frequency instability was mainly attributed to
the crystal glass substrate of the PBS. To compensate
for such, further effort will be made to place a crystal
glass substrate (W) of the same thickness as the PBS
coated by the anti-reflective film in the S sub-cavity. In
such case, we believe that the thermal disturbance to the
beat frequency will be reduced remarkably because it
will have little thermal difference when it is very near
and with the same thickness.

Other factors affect the performance of the force mea-
surement system. Firstly, the pushing and pulling effects
of the laser affect the linearity of the relation between the
change in the beat frequency and the change in the differ-
ence of the two sub-cavities’ optical path length, which is
calculated to be about $10^{-5}$. This value is small, thus
it can be ignored at present. Secondly, the frequency
difference lock-in phenomenon leads to the reduction of
the force measurement range. Nevertheless, the laser’s
lock-in phenomenon can be reduced and even eliminated
by means of a transverse magnetic field\cite{18}. 

In conclusion, compared with other laser transducers,
this type of laser sensor has some advantages such as
having operation stability and versatility. In virtue of
the sensitive gas in one sub-cavity being the first step
sensor in the laser transducer, the input signals do not
disturb the direction of the ray, thereby preventing the
operation of the laser to be affected. Furthermore, we
conclude that this new laser sensor has a better potential
perspective for extensive applications. With the develop-
ment of an appropriate mechanical structure, it can be
applied in the field of electronic weighing, precise
force measurement, inertial navigation, and vibration
measurement, especially for quick starting measurement
field. Besides, the laser transducer can be used in mea-
suring the refractive index and density of the transparent
medium by putting the sample in one sub-cavity (S sub-
cavity or P sub-cavity)\cite{17,19}, while the other sub-cavity
serves as the reference sub-cavity. A higher resolution of
the index and the density’s measurement is expected
with the use of the differential technique.

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