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Accuracy of Commercially Available Laser Measurement Systems

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This paper presents the results of measurements on the accuracy of commercially available laser measurement systems. After a short introduction the set-ups are described for measuring the laser wavelength and for checking the total measurement system. The first part is based on well known heterodyne measurements and the second is carried out by comparison with a well calibrated laser interferometer. Only one moving mirror is used in both measuring beams, so first order (Abbe) errors are avoided.

Results show that laser systems using wavelength stabilisation based on Zeeman-splitting are usually more accurate than the manufacturer claims. However, when automatic compensation for index of refraction is used, large errors can occur due to failure in temperature or pressure measurement.

Relative errors up to 1.4×10^{-6} were measured in some laser systems using two mode stabilisation, due to a wrong wavelength used in the electronic system.

The conclusion might be that laser measurement systems are very accurate length measuring instruments provided systematic errors are avoided by periodic calibration of emitted wavelength and automatic compensation system.

I. INTRODUCTION.

Since the He-Ne laser was introduced in 1961 many papers have been published about the use of this lightsource in metrology especially by interferometric measuring methods. In that case it is necessary to have a lightsource which emits a stable single wavelength. To get this stable wavelength several stabilization-technics were developed in the past 15 years and some are used today in commercially available laser measurement systems. All methods are based on comparing the emitted wavelength with an internal reference of the doppler broadened neon spectral line of the laser and are therefore subject to frequency changes of this spectral line.
During the last ten years some standards laboratories, and also the Metrology lab of TH-Eindhoven have developed lasersystems stabilized on external references e.g. absorbtion lines of CH_4 and J_2 [1, 2]. Longterm stability and reproducibility of these lasers are far superior to internal-reference stabilized lasers mentioned before. An earlier paper [3] gives the results of measurements of commercially available lasers by heterodyne-measurements (beatmeasurements) against an J_2-stabilized laser system.
Since then we have extended this measurement scheme by a setup for checking the complete laser measurement system including counting, calculation and refraction index measurement. The total measurementscheme is splitup in the following steps:

A. Measurement of the laserwavelength, stability and reproducibility by beatmeasurements.
B. Checking the counting system.
C. Checking the calculation system.
D. Checking the automatic compensation system.

The next paragraphs will give a more detailed description of the method and the results obtained.

II. EXPERIMENTAL SETUP.

The wavelength of the laser can be determined by frequency measurement. By a beatmeasurement the frequency difference is detected between the laser to be calibrated and the J_2-stabilized laser locked on the so-called "d"-dip which has a frequency f_d = 473612380,5 MHz [4]. With the recommended value for the speed of light C [5] the wavelength λ_d can be calculated. The beat measurement offers a frequency difference Δf so the vacuum wavelength λ_v of the laser system to be calibrated can be calculated from $\lambda_d = \frac{C}{fd}$ (I) and $\lambda_v = \lambda_d + \Delta\lambda$ (II) where $\Delta\lambda = -\lambda_d \cdot \frac{\Delta f}{f_d}$ (III). Figure 1 gives the schematic diagram of the beatmeasurements. The mirror telescope is used to reduce the beam diameter of laser 'B' to the same value as the beam of laser 'A' to get an optimal beat signal.
In this experiment the warming up phenomena are measured from a cold start of the lasersystem to be measured. In this case the measured frequency difference is fed to a digital to analog converter and plotted. Some results are given in [3]. The reproducibility is measured by repeating this measurement over several days. From each measurement the mean wavelength is calculated from cold start but after sufficient warmingup time [3].
The counting system is checked against a well calibrated lasermeasurement system LI using the same light path. Figure 2 shows the schematic diagram of the apparatus.
This setup is used for lasersystems of the same manufacturer (Zeeman splitting stabilization) [3]: if the measurementsystems are different the setup is somewhat modified.
Radiation from lasersystem LI is directed to the remote interferometer R and after splitting reflected back by corner cubes C_1 and C_2 into LI. LI is adjusted so the beam to C_2 is parallel to the guideway A. This adjustment is carried out by mounting a quadrant photodetector instead of C_2 and measuring the beam position at different places by moving carriage W.
Then, after reflection by S, the beam of lasersystem LII is sent to R. This beam is aligned in the same way as that of laser LI. Now the photodetector is replaced by the cornercube C_2 and both beams are falling on C_2: one in a horizontal the other in a vertical plane.

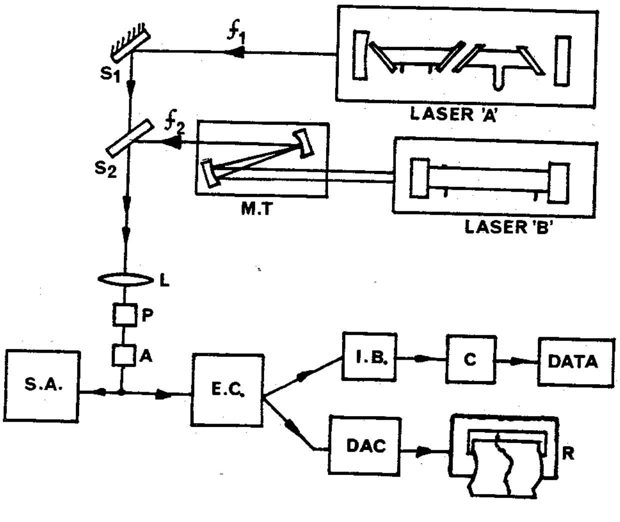

FIG 1

FREQUENCY MEASUREMENT OF LASERS

S_1 : flat mirror ; S_2 : partly transmitting mirror ; MT : mirror telescope ; L : lens ; P : photodiode ; A : amplifier ; SA : spectrum analyser ; E.C. : electronic counter ; I.B. : interface bus ; C : small computer ; DAC : Digital to Analog Converter ; R : recorder.

Distance between the beams is not more then about 15 mm so they are subject to the same conditions of temperature, pressure and humidity. Alignment errors will be within 0,5 mm over the measuring length of 2m so second order cosine errors will be less then 0,1 µm over this length.
First order Abbe-errors are absent, of course, since one corner-cube mirror is used for both systems.
When the lasersystems are of different types it is often not possible to use the same interferometer cube for both systems. In that case the setup is some what changed as shown in Fig. 3. Now an additional mirror S is used as indicated in the diagram. Of course, this setup can also be used if the lasersystem has an internal interferometer cube, however such interferometer systems were not offered us for calibration. Mirror S has a special prepared surface partly covered by an aluminium coating and partly transparent because some lasersystems have special polarization properties which should not be disturbed.
Distances from S to RI and S to RII are nearly the same but still some influence of temperature is possible during the measurements. So we keep temperature fluctuations well below 0.05 K. The temperature in the enclosed setup is measured by a platinum resistance thermometer which is connected to a measuring system using a Diesselhorst-compensator.
The pressure is measured by a null-balance metallic barometer (system Paulin) calibrated against a mercury barometer (Fortin type) while humidity is measured by a dry and wet bulb thermometer.

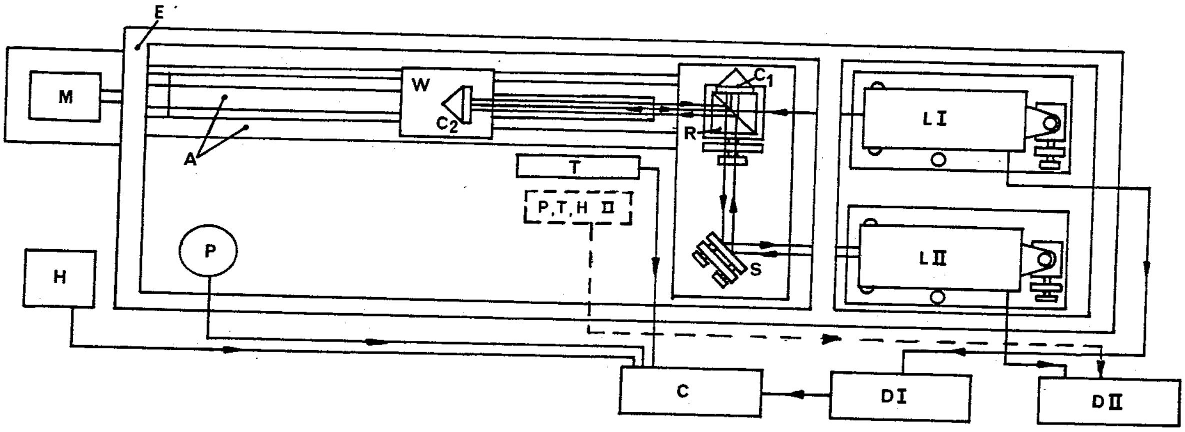

FIG 2

SET UP FOR LASER MEASUREMENT SYSTEM CALIBRATION OF SAME TYPE

LI : reference laser system
DI : display system LI
C_1, C_2 : corner cube mirrors
S : adjustable mirror
W : carriage
A : leadscrew + guideway
M : motor + control
E : polystirene enclosure

LII : lasersystem to be calibrated
DII : display system LII
R : remote interferometer
T : resistance thermometer
P : pressure measurement
H : humidity measurement
C : computer

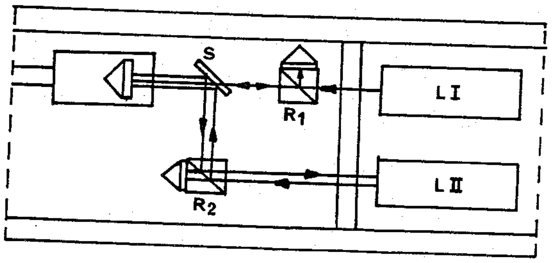

FIG 3

LASER MEASUREMENT SYSTEM CALIBRATION FOR SYSTEMS OF DIFFERENT TYPE

RI : remote interferometer system LI
RII : remote interferometer system LII
S : semi reflecting mirror

III. MEASURING PROCEDURE.

After the measurement of wavelength, stability and reproducibility of the ligthsource the complete laser measurement system is compared against our (THE) laser measurement system in the setup described before.
As is well known the measuring length L may be calculated from: $L = K \cdot \frac{\lambda_a}{4}$ (IV). Here λ_a is the actual wavelength in air calculated from: $\lambda_a = \frac{\lambda_v}{n}$ (V). λ_v is calculated from (I), (II) and (III). n is the index of refraction of air as calculated by Edléns formula [6].
All the laser measurement systems we checked can operate in two modes. In one mode the display shows the displacement in units of $\frac{\lambda}{4}$ ('k' value) while in the other mode the display offers the displacement in normal units (mm or inch). The 'k'-values of both lasersystems should by nearly the same, a small difference due to different wavelength [3] and alignment errors is allowed, over the whole measuring range. We have found no differences larger then one or two counts when the interferometers were funtioning correctly. Figure 4 shows a graph of comparisons with three laser measurement systems.

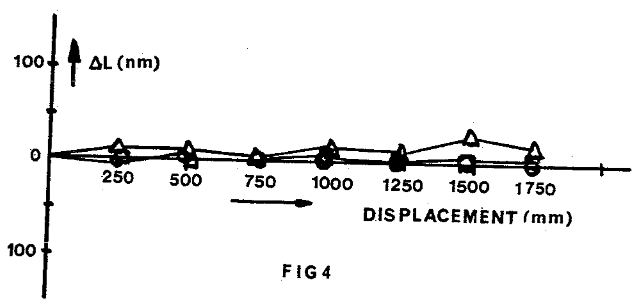

FIG 4

The length difference Δl is calculated by multiplying the measured 'k'-values by their actual vacuum wavelengths. The measured differences Δl are caused by small cosine and reading errors. As expected these differences are very small since there is no influence of the index of refraction.
The reference laser measurement system (THE) was used in the 'k'-value mode in all measurements. Temperature, pressure and humidity, to calculate the actual index of refraction of air, were measured as described before. Temperature measurement was within 0.05 k, pressure within 20 Pa and humidity within 5%. So the relative errors in our system will be less then 2.10^{-7}.
In the next step we have compared our system in this setup against other laser measurement systems. Some had a manual compensation system for refraction index changes (thumbwheels) but most systems were using automatic compensation systems. Figure 5 shows absolute values of measured differences of measurements on seven different systems.

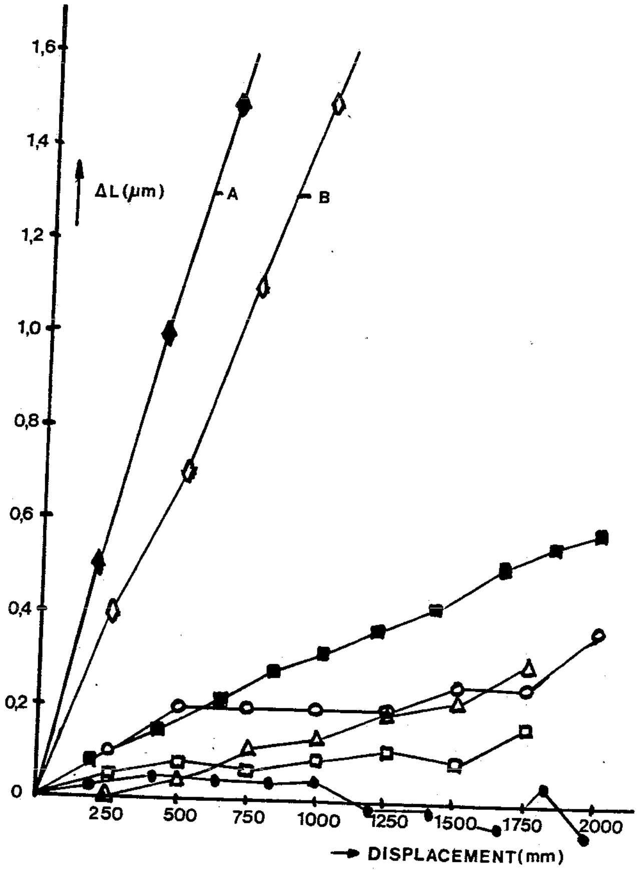

FIG 5

Most of the results are within claimed accuracies (1 . 10^{-6}) but some systems showed larger errors. In one system, using two mode stabilization [3], the automatic compensation system did not funtioning correctly although the display suggested correct operation (curve A). Curve B showed the behaviour of another system based on two mode stabilization with mode separation of 680 MHz. The radiation of one mode was as usual used in the interferometer but the built in microcomputer used the wavelength belonging to the other mode for calculation so a relative error of $\frac{\Delta f}{f} = \frac{6,8 \,.\, 10^8}{5 \,.\, 10^{14}} = 1,4 \,.\, 10^{-6}$ resulted as indicated by curve B. This error can occur easily since the mode used is determined by the angular position of the plasmatube around the longitudinal axis. The third case of a wrong measurement arose from a Zeeman stabilized laser system with automatic compensation for changes in index of refraction. The display indicated a mal-function on pressure measurement but the computer used these values in calculations. The result is given in figure 6 since it could not be fitted in the graph in figure 5. For the same laser measurement system the results are given for a measurement with manual refraction index compensation.

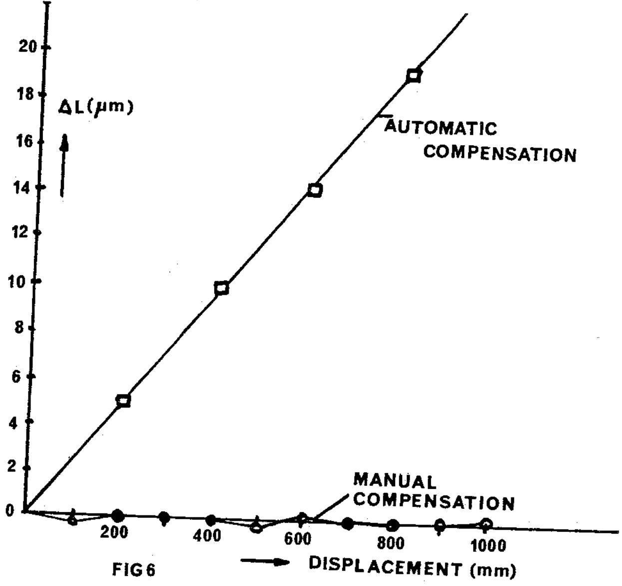

FIG 6

IV. CONCLUSIONS.

The setup described here proves to be of a great value for calibration of laser measurement systems which are used increasingly in industry. Inspection of wavelength by beat-measurements offers information about the stabilization system and emitted wavelength. As described before we have found the use of wrong wavelength in a two mode stabilized laser system. All the laser systems based on Zeeman stabilization we have measured (all owned in the Netherlands) showed a good stabilization but in most cases the warming up time was somewhat longer then the manufacturer suggested.
In the second part of the calibrations we have measured the overall behaviour of the laser systems. In some cases we found extreme errors due to failures in the automatic compensation of refraction index. When manual compensation was used, assuming the wavelength used was correct, relative errors did nod exceed 3 . 10^{-7} which is better then the manufacturers claims.
The best accuracies can be reached, especially with Zeeman stabilized laser systems, by using the $\frac{\lambda}{4}$ counting mode, and calculating the displacement from measurements of wavelength, pressure, temperature and humidity as described in paragraph III. Of cource, these values have to be measured with sufficient accuracy [6].
In general we may conclude that laser measurement systems are very accurate measuring instruments but it is absolute necessary to calibrate them periodiccally. A check of the frequency behaviour only is insufficient and carefull calibration of automatic compensation system for index of refraction is also needed.

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