A Doppler Laser Radar Diagnostic Technique For Characterization of Free-Surface Flows[1]

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Abstract-- Freely flowing low Z liquid metals such as lithium and gallium are being investigated as plasma facing walls in magnetic fusion devices because of their superior heat transfer properties during normal plasma operation and self-healing characteristics during plasma disruptions. However, creating and maintaining such liquid wall surfaces inside a fusion chamber is a major challenge and experiments are in progress at UCLA, Princeton, and ANL, to find solutions to this problem. Measurement of flow characteristics in such experiments is difficult because of the fusion plasma environment involving high vacuum, high temperature, and high magnetic field. A technique using frequency modulated coherent laser radar (FM CLR) is described for non-intrusive characterization of free-surface flows. The technique involves Doppler corrected range and velocity measurements at the flowing surface, using a linearly modulated CLR. The principles behind the measurement are described and the results from a proof-of-principle experiment are given.

I. INTRODUCTION

Frequency modulated coherent laser radar has been used successfully for precision metrology and mapping of plasma facing surfaces in fusion experiments [1-4]. Here it is shown that the technique can also be developed for free-surface flow characterization of liquid metals (LM). The non-intrusive and remotely controllable nature of the measurement technique makes it a powerful diagnostic tool for fusion applications.

In the FM CLR developed for precision metrology and mapping of surfaces, a linearly frequency modulated laser beam is injected into the fiber optic CLR circuit. Part of the laser beam is diverted to a reference arm interferometer that serves as an internal length standard. The remainder of the output travels to the signal path where a portion is split off to form the local oscillator (LO) delay path. Most of the laser light is directed to the target, through a system that contains the focusing and scanning optics. The signal reflected off the target is recaptured by the focusing optics and combined with the light in the LO path. The mixing process produces a beat frequency f_b, which is proportional to the transit time τ.

$$f_b = M_f \tau \qquad (1)$$

where, the proportionality constant M_f is the frequency modulation rate and the transit time is given by:

$$\tau = 2\mathbf{R}/\mathbf{c} \qquad (2)$$

where **R** is the range and **c** is the velocity of light. Thus, for a fixed target, the range is given by:

$$\mathbf{R} = [\mathbf{c}/2M_f]\, f_b \qquad (3)$$

Fig. 1 schematically illustrates the concept. In this figure, the received signal is shown as representative from a stationary target.

When the target is moving, Doppler corrections must be applied to the measurements. The Doppler shift in frequency due to the velocity of a moving object is given by:

$$\mathbf{f} = \mathbf{f}_0[(1+\mathbf{v}/\mathbf{c})/(1-(\mathbf{v}/\mathbf{c})^2)^{0.5}] \qquad (4)$$

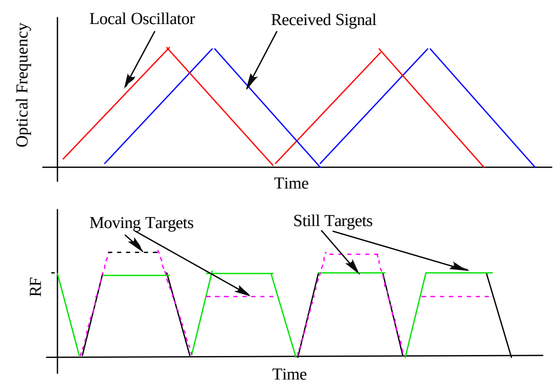

Fig. 1 Frequency vs time graphs for the local oscillator, signal, and the resultant beat frequency (marked RF).

where, **f** is the observed frequency, $\mathbf{f_0}$ is the source frequency, and **v** is the relative velocity of the source in the direction of the beam (considered positive when the source is approaching). For low relative velocities, the above expression reduces to:

$$(\mathbf{f} - \mathbf{f_0})/\mathbf{f_0} = \Delta f/\mathbf{f_0} = \mathbf{v}/\mathbf{c} \qquad (5)$$

where $\Delta f = \mathbf{f} - \mathbf{f_0}$ is the Doppler frequency shift due to the relative velocity **v** of the object.

$$\Delta f = \mathbf{v}\, \mathbf{f_0}/\mathbf{c} = \mathbf{v}/\boldsymbol{\lambda_0} \qquad (6)$$

where $\boldsymbol{\lambda_0}$ is the wavelength of the source.

For a moving target, the frequency shift is composed of two parts: (1) the frequency shift introduced by the modulator

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during the transit time to and from the target, and (2) the frequency shift due to the velocity component of the object. The beat frequencies during the up-shift (f_{bu}) and down-shift (f_{bd}) parts of the waveform shown in Fig. 1 are given by:

$$f_{bu} = M_f\,(2\mathbf{R}/\mathbf{c}) + \mathbf{v}/\boldsymbol{\lambda}_0 \qquad (7)$$

$$f_{bd} = -\,M_f\,(2\mathbf{R}/\mathbf{c}) + \mathbf{v}/\boldsymbol{\lambda}_0 \qquad (8)$$

It follows from equations 7 and 8 that the relative velocity is:

$$\mathbf{v} = \boldsymbol{\lambda}_0\,(f_{bu} + f_{bd})/2 \qquad (9)$$

and the Doppler corrected range is:

$$\mathbf{R} = (f_{bu} - f_{bd})\,[\mathbf{c}/2M_f] \qquad (10)$$

For the prototype FM CLR, the frequency to range conversion factor, [$\mathbf{c}/2M_f$)], is 1 m per 500 kHz or 2µm/Hz.

The prototype FM CLR used to illustrate the measuring concept is designed primarily for precision range measurements on stationary targets. Fast Fourier transform techniques (FFT) are used for the detection and analysis of frequency components that are of interest even when accompanied by strong noise. In this situation, if the target velocity changes rapidly (as in a fast vibrating target) the digital signal processing limits the vibrational amplitude that can be measured. A second limit for the technique arises from the instantaneous bandwidth of the digital signal processor (200 kHz for the FM CLR). Fig. 2 shows these limitations graphically.

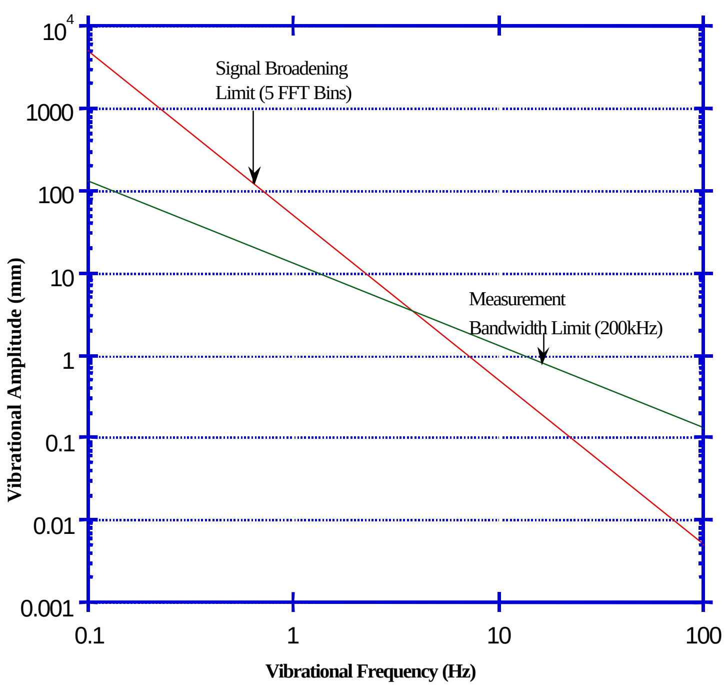

Fig. 2 Detection limitations of the prototype FM CLR due to signal broadening and bandwidth limitations of the digital processing electronics.

II. FREE SURFACE FLOW CHARACTERIZATION

A. Diagnostic Configuration

For measurements of flow velocity and liquid film thickness, the FM CLR device can be setup outside the vacuum chamber with the laser beam directed at the target through a vacuum window (Fig. 3). If absolute measurements are needed, the correction for the window can be applied as shown in Fig. 4. By specifying range limits in the FM CLR control computer, the presence of the window can be ignored and the beam can be focused at an object beyond the window. This way, physical contact with the vacuum vessel can be completely avoided thereby eliminating potential vibration effects.

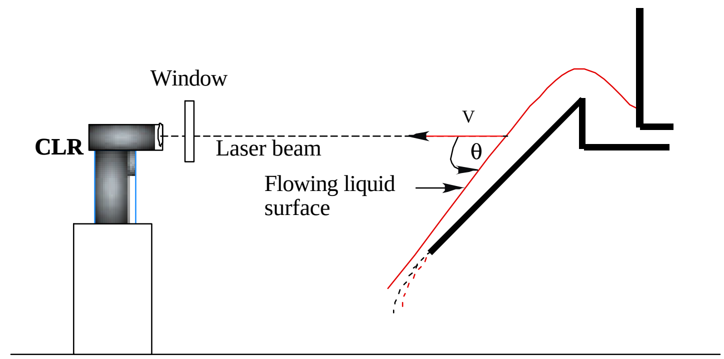

Fig. 3 Schematic of liquid metal flow characterization setup.

To illustrate that measurements can be made through a window, range measurements were conducted through a thick plexiglass window. Results are shown in Fig. 4. The results also show that when absolute range measurements are needed, the range measurements obtained through the window can be corrected for the optical thickness of the window. While an optical probe head could be designed for in-vessel measurements, such a scheme would be affected by vibration noise transmitted from the vessel to the probe head, and coating of optical components within the head by impurities generated at the wall.

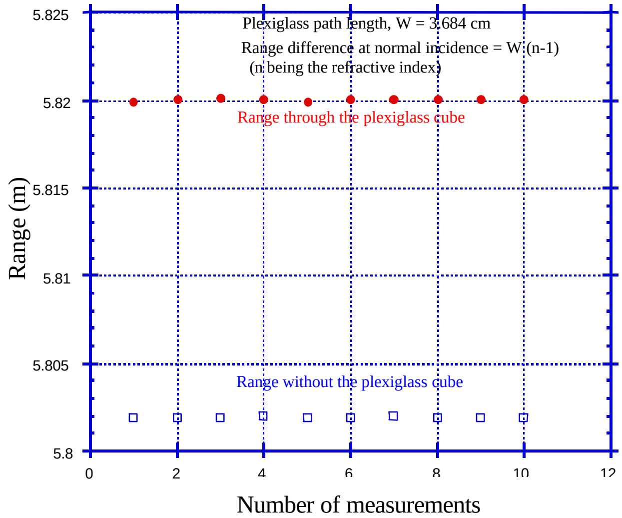

Fig. 4 Results of range measurements through a window.

B. Proof-of-principle Measurement of Free-Surface Flow

In order to illustrate the concept of free surface flow velocity measurements, the prototype FM CLR was aimed at the surface of a moving roll of chart recorder (the moving paper surface simulating the free-surface flow of liquid metal film). Fig. 5 shows the results. The results are in agreement with the chart velocity when the geometry of the measuring configuration is taken into account. Note that both chart recorder speed limitation as well as the bandwidth limitations of the signal processor prevented measurement of higher velocities. But the basic concept is validated by this measurement.

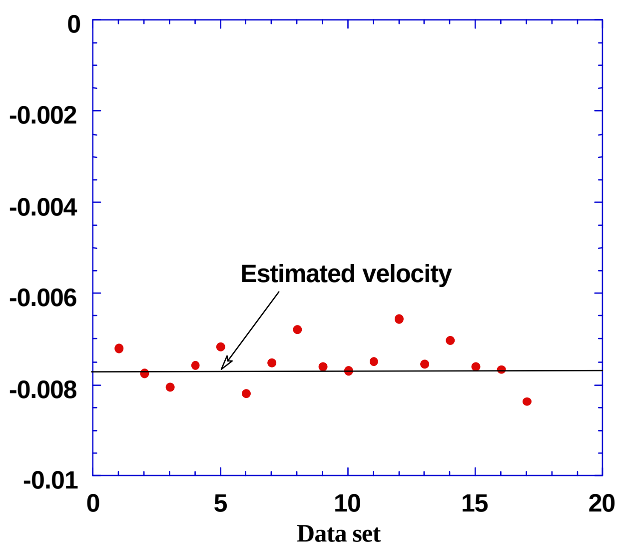

Fig. 5 Measured velocity (dots) compared with velocity component estimated from the chart speed.

III. Conclusion

We have demonstrated that the FM CLR technique can be applied for non-intrusive measurement of range as well as velocity of targets. The technique can be developed for free-surface flow measurements of liquid metals in fusion environment. However, significant R&D would be needed in meeting all the anticipated requirements for the liquid metal research.

References

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