大規模空間非接触計測器 APDIS MV4x0 レーザーレーダーの開発

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Development of the APDIS MV4x0 Laser Radar Large-Volume, Non-Contact Measuring System

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自動車業界の生産現場の要求は高度化し，信頼性はもとより高性能で高速な計測技術が求められている．それらの要求にこたえるべく，ニコンの光学コア技術とニコンメトロロジーのレーザー計測技術を融合した「APDIS シリーズ」を2020年10月にリリースした．本稿では本製品 APDIS の基礎原理となる部分に加え，APDIS シリーズとして実現した新たな開発要素について説明する．

The demands of production line metrology in the automotive industry are becoming greater and more challenging. High accuracy and high-speed dimensional part measurement as well as high reliability are key requirements for inspection. In order to meet these high expectations, we released the APDIS series in October 2020, which combines both Nikon's core optical technology and Nikon Metrology's laser radar technology. This paper describes the new technical features we developed and implemented in APDIS in addition to the product's basic principal of operation.

Key words 三次元計測機，非接触，周波数変調，レーザーレーダー，自動車部品検査
coordinate-measuring machine (CMM), non-contact, frequency modulated continuous wave (FMCW), Laser Radar, car body inspection

1 Introduction

In October 2020, Nikon released the APDIS MV4x0, the next generation of the Nikon Laser Radar. The MV430 and MV450 measurement systems are used for fast, automated and non-contact inspection of objects ranging from smaller components such as a car door to complete large assemblies such as commercial aircraft. It achieves this through a unique application of a non-contact, accurate laser-based measurement technology overcoming the limitations of traditional monolithic or portable metrology systems.

The ability to measure detail at a distance, without the need for handheld probes, targets or surface preparation means APDIS is ideally suited for repetitive, complex, hard to reach, delicate and labor-intensive inspection tasks, covering a huge range of manufacturing, industry and research applications. This paper describes various innovative features that are incorporated into the system.

2 Development Background

The heart of the APDIS system is a Frequency Modulated Continuous Wave (FMCW) coherent laser radar that uses a diode laser as its source. A waveform is used to change the frequency of the laser directly by modulating the laser's injection current, resulting in linear modulation. This type of modulation is often referred to as a chirp. The frequency can be expressed as a function of time in the following manner:

$$f(t) = f_0 + (\Delta f/\Delta t)t \quad (1)$$

Where f_0 is the center frequency of the laser. By using a lensing system, the modulated beam is focused at a target, where it is scattered and recollected by the optics after a round trip transit time t. The distance to the target, R, is calculated using the relationship:

$$\tau = 2R/c \quad (2)$$

where c is the velocity of light.

In an FMCW laser radar device, a portion of the transmitted beam is split from the incident light wave and forms the local oscillator (LO), which is then mixed with the returned (signal path) energy. In a coherent laser radar, the beat frequency produced will be equal to:

$$Beat\ Frequency = f(t) - f(t+\tau) = (\Delta f/\Delta t)\tau \quad (3)$$

The beat frequency is measured electronically and used to calculate the distance to the target R:

$$R = c * Beat\ Frequency/(2(\Delta f/\Delta t)) \quad (4)$$

In early Frequency Modulated (FM) devices, the accuracy of range measurement was limited by the linearity of the frequency modulation over the counting interval. For example, if the target is one meter distant, a linearity of one part per thousand is necessary to ensure 1 mm accuracy. Advanced techniques employed in the Nikon Laser Radars enable a high degree of linearity. In addition, these techniques can detect and compensate for real time variances from linearity. This enables range measurements with single digit micron precision.

FMCW radars are largely immune to ambient lighting conditions and changes in surface reflectivity because they rely only on the beat frequency, which is not dependent upon signal amplitude, to calculate range. This enables the system to make reliable measurements with as little as one picowatt of returned laser energy. This corresponds to a nine order-of-magnitude dynamic range in sensitivity.

Fig. 1 depicts the linear frequency modulation, or "chirp", together with the corresponding "beat" frequency that results from combining the outgoing and incoming light signals. The laser base frequency is approximately 200 terahertz. The "beat" frequency is in the 10 MHz range. If the surface being measured is moving relative to the laser light source, the beat frequencies corresponding to laser upsweeps will be different from the beat frequencies corresponding to the downsweeps, due to Doppler frequency shifting. Measuring the frequency difference between these signals enables a determination of velocity to be made.

For precision measurements it is necessary to include a reference standard both for absolute ranging accuracy and

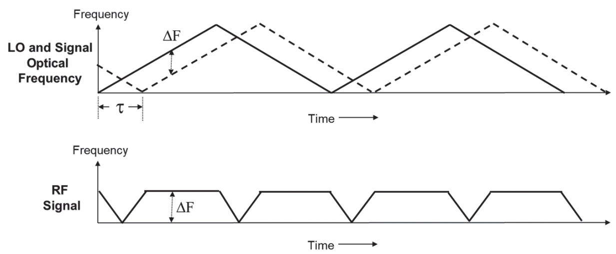

Fig. 1 Laser optical frequency and heterodyned RF signal of coherent laser radar.

to help linearize the laser's chirp waveform. For the internal reference standard, the light from an IR laser is split into two fibers by means of a fiber coupler (See Reference Arm in Fig. 2.). One path is sent to the mixing and focusing optics and used to measure range. The other path is directed to the reference standard that consists of an input fiber optic coupler, which splits the light into two fiber paths and an output fiber coupler, which recombines the light into a single fiber. The two paths of fiber between the two couplers are mismatched in length by several meters such that a laser radar signal is detected on the reference detector. This reference Mach Zehnder interferometer formed by the two couplers and the fiber between them is kept in a temperature-controlled container to prevent the fiber lengths from changing.

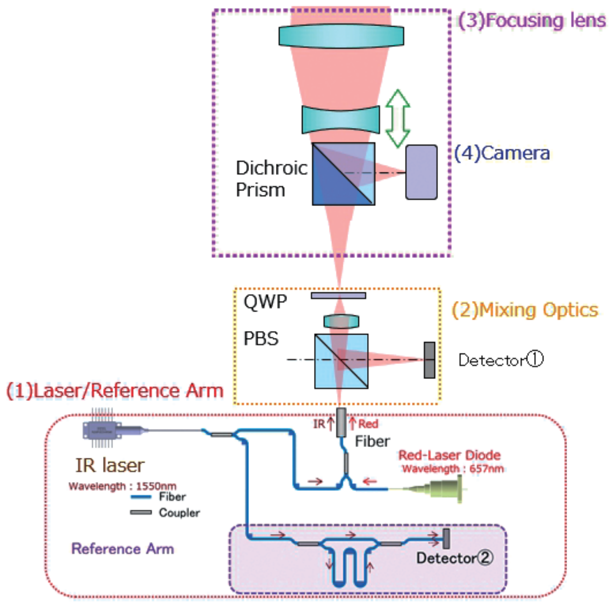

Fig. 2 Optics overview

The APDIS system has several improvements over previous versions of the laser radar. The first is the incorporation of a compact mixing optics assembly that is insensitive to environmental changes (temperature, etc.). Previous laser radars used a fiber optic circuit to perform the mixing function. This circuit was more costly and needed to be thermally controlled to maintain measurement stability. The second improvement is the inclusion of a high-resolution video camera in a boresighted, confocal relationship with the radar's measurement beam. The radar and the camera utilize a common focusing system allowing for a precise relationship between the two sensors. Another improvement is the physical sealing of the system to prevent water and dust egress. This is especially important in use in a factory environment. Finally, the capability to remotely measure velocity (vibrations) as well as range was incorporated to provide additional data to the user. These improvements are described in more detail below.

3 Optical Design

The optical system of the APDIS laser radar consists of (1) the light source/reference arm unit, (2) the mixing optics or interferometer unit, (3) the focusing lens and (4) boresighted camera (Fig. 2).

The light source unit uses a 1550 nm diode laser to produce the frequency-modulated measurement light. This light is split between the reference interferometer discussed above and the measurement path. In addition, light from a red laser diode is combined with the IR laser light to provide the user with a visible indication of the output beam position. This red spot, when focused on a target, can be seen visually by the user both in the video display and on the actual target.

4 Mixing Optics (Interferometer Unit)

The mixing optics of the APDIS laser radar eliminates many of the fiber optic components used in previous systems. The miniature mixing optics are shown in Fig. 3. The laser light is transported to the mixing optics via a Polarization Maintaining (PM) fiber. The laser light exits the fiber and passes through a polarizing beamsplitter (PBS) which is fabricated to pass one linear polarization state and reflect the other polarization state. The light emitted from the fiber is in the linear polarization state that passes through the PBS. The light then passes through a focusing lens and then through a quarter wave plate retarder (QWP). The QWP is aligned such that the linearly polarized light is converted to circularly polarized light (for example right circularly polarized light.) In addition, the QWP has an antireflection coating on the first surface (the surface first encountered by the beam) and a partially reflective coating on second surface (the surface encountered by the beam after it has passed through the QWP). The QWP is also positioned such that the focused spot coincides with the partially reflective surface. The light that is reflected back becomes the LO path beam while the light that passes through the QWP becomes the signal path beam. This beam is then focused onto a target to be measured via the focusing optics. The LO path light, upon reflecting from the QWP surface, switches its circular polarization state to left circularly polarized light and then is converted by the second pass through the QWP to an orthogonal linear polarization state. This light is refocused by the focusing lens and is reflected by the PBS to a photodetector. Similarly the signal light that reflects off a target also undergoes a change in circular polarization state to left circularly polarized and, after passing back through the QWP, also is converted to the orthogonal linear polarization state and is reflected by the PBS to the sensor at which point it optically mixes with the LO light to generate the radar signal. The combination of the focusing lens and the QWP forms a Cats-eye retroreflector which ensures alignment between the LO and signal paths and provides for a stable optical configuration. Also, since the LO path is a subset of the signal path, any drift in the position of the mixing optics affect both paths equally, eliminating the temperature sensitive drift problem of the previous systems. In older systems, the mixing interferometer is fabricated from fiber optic components and housed in a temperature-controlled module, which hinders miniaturization. Therefore, this cat's eye arrangement is used to reduce the number of parts and realize miniaturization.

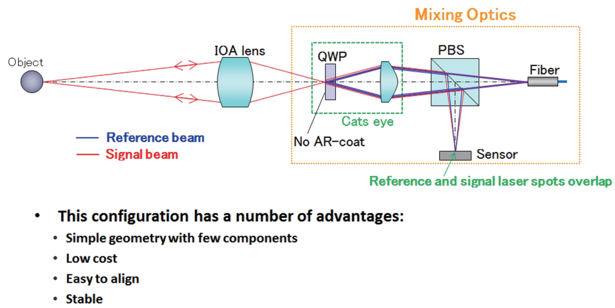

Fig. 3 Mixing Optics.

As to the stability of such an assembly, Fig. 4 shows the dependence of the laser spot position on the sensor as a function of QWP tilt and offset. As can be seen, if the QWP surface coincides with the image plane of the lens, the spot position is independent of QWP angle.

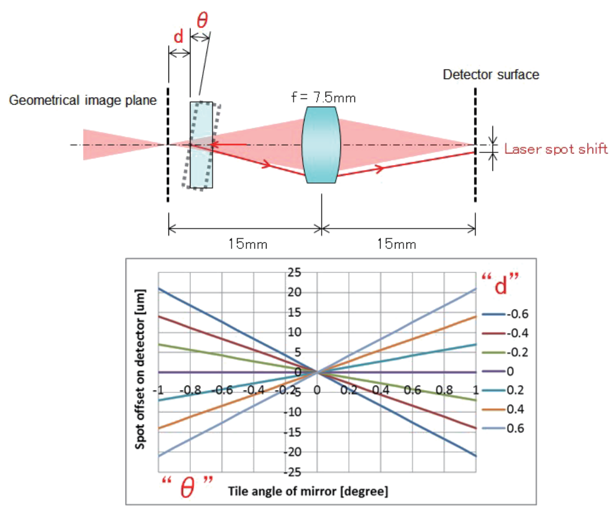

Fig. 4 Sensitivity of the mixing optics to misalignment.

Fig. 5 shows the effect of beam shift between the signal and the LO spots on the laser radar signal. As can be seen, a 7um beam shift produces a 1.5 db loss in signal level. This is an acceptable loss for such measurement systems. This is the same loss that would be produced by a 0.4 mm QWP offset combined with a 0.6 degree QWP tilt. The manufacture and assembly of an optical mixing assembly to within these tolerances is easily accomplished.

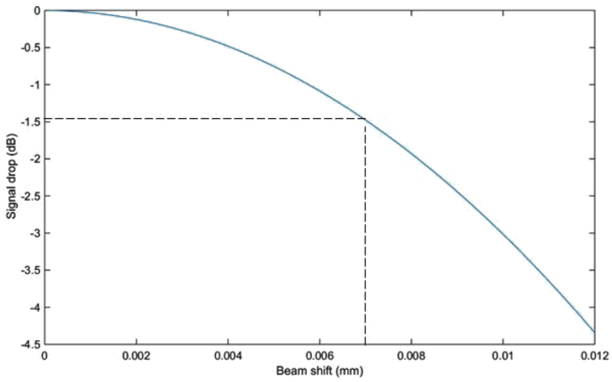

Fig. 5 Laser Radar signal loss due to beam shift.

5 Objective Lens and Boresight Camera

One of the improvements of the APDIS laser radar over previous models is the reduction of the minimum measurement range from 1 meter to 0.5 meters. This reduction in stand-off distance improves the usability of the instrument in factory assembly line settings where space is at a premium. The objective, or focusing, lens developed for APDIS is an optical system that supports this reduced range measurement. In addition, it also supports both the IR light for measurement and the visible camera wavelength range. In the past, the focusing optical system of the measurement light and the boresight camera were separate optical systems, and the optical paths were separated by a dichroic mirror. Therefore, since each optical system had its own focusing mechanism, it was impossible to match the measurement point with the camera field of view. In order to overcome this drawback, the APDIS lens has a dichroic prism placed between the focusing lens and the intermediate image plane (QWP surface) to separate the visible wavelength and the measurement wavelength. Since the focusing mechanism is shared by this configuration, the measurement point and the field of view of the boresight camera can be matched. Therefore, measurement support using object recognition based on camera images has become achievable.

It is possible to irradiate the measurement light and the red laser light for visual recognition from the fiber end, but if the axial chromatic aberration is completely corrected, the spot of the red light becomes too small and the visibility deteriorates, so by intentionally leaving the axial chromatic aberration, visibility is ensured. Another characteristic point is the dichroic prism. A general dichroic prism is a cube type with a slope of 45 degrees, but the APDIS dichroic prism has a slope at an angle of 30 degrees with respect to the incident optical axis (Fig. 6). As a result, the angle range of incident on the slope can be reduced, so that the polarization dependence of the transmittance/reflectance in the visible light region of the dichroic film can be reduced. If the polarization dependence of the dichroic film is large, the appearance of the camera image will change because the reflectance changes depending on the polarization direction due to the change in the angle of incidence on the deflection mirror when observing points with different elevation/azimuth angles. In order to suppress this problem, a prism with a special shape (Fig. 6) was adopted.

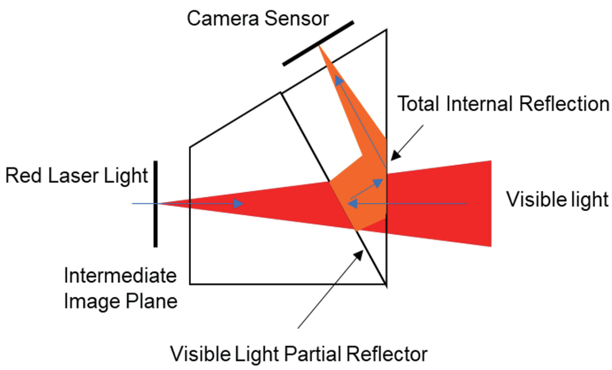

Fig. 6 Dichroic prism.

6 Camera Resolution

In past versions of the Laser Radar (LR) a collinear camera was in the unit with the following limitations: (a) the camera was an inexpensive surveillance camera whose calibration parameters changed with orientation to gravity and was environmentally sensitive (temperature), and (b) architecturally the camera and the LR data were brought together at too high a level to allow real time coordination between the camera and the LR data. The APDIS Laser Radar incorporates a metrology camera which (a) shares the same focusing optics with the LR measurements creating a confocal Laser Radar (cLR) and metrology relationship (6DOF) between the camera and the Laser Radar, (b) is high definition, and (c) is now tied to the LR data at a low level in the architecture minimizing the latency between the data allowing real time coordination of the LR and camera data.

The APDIS video camera is a 4.2 Megapixel (2048x2048) CMOS sensor in an RGB Bayer Matrix. As shown in Fig. 7, this sensor covers a 7degree field-of-view (FOV). However, this FOV is truncated to 5 degrees to remove the edges of radar's circular output aperture so the effective camera resolution is about 1400x1400 pixels. Each pixel covers 63uradians of the image scene. The camera sensor mount was designed to maximize the stability between the Laser Radar and the video image. The APDIS system is vastly superior in this respect as compared to previous systems. APDIS retains sub-pixel stability in alignment regardless of the radar orientation. This is important as the system is often robot mounted in order to facilitate factory measurements. In addition, the alignment is stable to less than 2 pixels over the 5℃ to 40℃ operational temperature range of the radar.

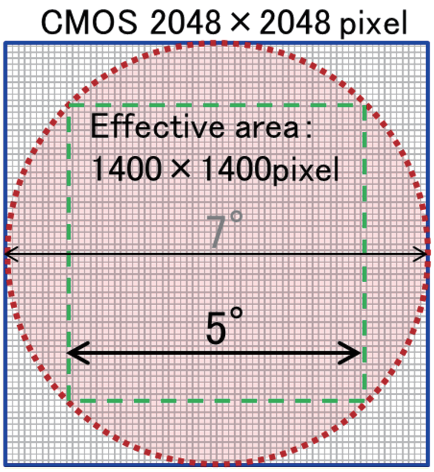

Fig. 7　Camera FOV.

Using the two measurement modes (LR and camera) in a confocal Laser Radar allows the LR to be pointed to optimally measure the feature of interest. Additionally, a low latency data interface allows real time algorithms and the tracking of features identifiable in the camera.

A calibrated camera can be viewed as an angle measurement device where the azimuth and elevation of every pixel in the picture can be determined. With the LR and the camera having a confocal relationship it simplifies the use of the range measurement to provide scale to the photo. This relationship allows the center pixel of the camera to be directly related to XYZ_{LR}. It cannot be guaranteed that the projection of the camera focal plane to the scene is perpendicular to the central ray of the Laser Radar. This relationship can be determined through a calibration process. With the calibrated camera planer features can be measured directly by the camera once the range is determined by the Laser Radar. The same can be said for features with known geometry, such as spheres.

7 IP54 Rating

The Protection against Ingress of fluids and solids into instrument packaging is a key feature of the APDIS system because of the harsh industrial environments required by automotive applications. The protection rating of 'IP54' was found adequate for these requirements. These ratings are determined as defined by industry standards defined by IEC 60529:1989+AMD1:1999+AMD2:2013 CSV - Degrees of protection provided by enclosures (IP Code) . The first number identifies protection against solids like dust and metal debris and the second number identifies protection against fluids like water. Fig. 8 describes rating derivation for IP54 rating guide.

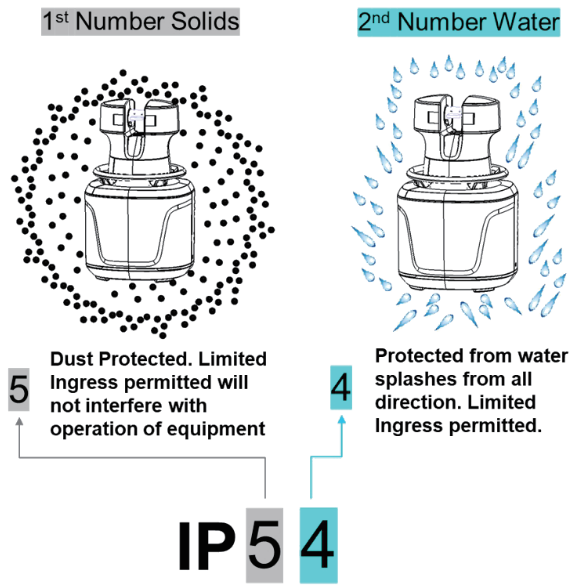

Fig. 8　IP54 Rating definition.

The design strategy for achieving the IP54 rating was developed based on type of interfaces across the APDIS design. (Fig. 9)

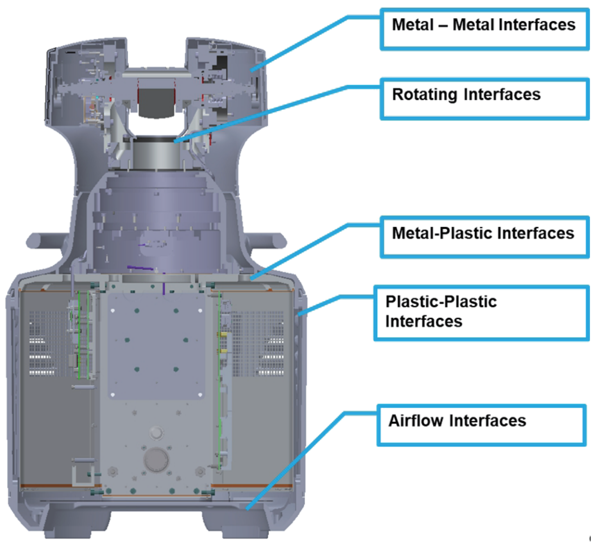

Fig. 9　APDIS cross-section showing various interfaces.

There were 3 main strategies for these interfaces.

a) Metal to metal interfaces used a technique to minimize interface gaps to less than 1mm and application of hydrophobic coating to prevent ingress of water and dust. Labyrinth structures were also used to create a sufficient seal. Rotating interfaces on the APDIS pointing mirror assembly had very small interface gaps augmented by light weight lubricant grease to form a hydrophobic and dust barrier.

b) Plastic to metal and plastic to plastic interfaces used a variety of custom gaskets strategically applied to prevent or minimize ingress of water or dust. Some of the materials were open/closed cell foams or EPDM type material. Fasteners with O-ring were also used at critical locations (Fig. 10). The selection of gasket material was particularly impacted by interface geometry, fastening methods and location on APDIS.

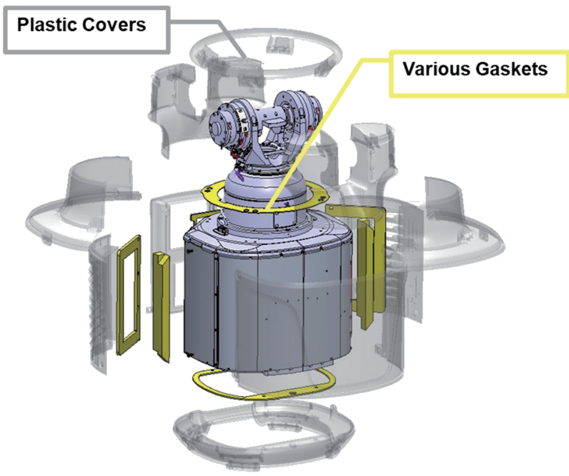

Fig. 10 Exploded view of external covers and various custom gaskets.

Fig. 11 APDIS after IP5X test.

Fig. 12 ADPIS after the IPX4 testing.

c) Interfaces where air flow for thermal management was require, water ingress was not completely avoidable. Here special vent panel materials and geometry which are hydrophobic were used. Strategically placed vent holes that facilitate purging of impressed fluids in only one direction.

Another strategy used was to incrementally design and test (in collaboration with the industrial design team responsible for external covers) using internal test methods that incorporated water detection paper and glycol-based smoke generator to detect ingress and leakages in interfaces.

The APDIS system tested showed no ingress dust ingress during IEC 60429 IP5X testing in locations which were sealed using techniques implemented above (Fig. 11).

APDIS system tested had minimum ingress into expected areas. The purge holes, and vent panels performed well to keep gasketed interfaces intact and prevent ingress of water during IEC 60529 testing for IPX4 standard (Fig. 12).

Ingress Protection is a key requirement for Automotive shop floor metrology where fluid splashes, welding and other process fumes and dust present hazards to measuring equipment and impact productivity and down time. The APDIS design strategies render the system very robust against such hazards by achieving the IEC 60529 IP54 rating.

8 Vibration Measurement Feature

As mentioned previously, if the surface being measured is moving relative to the laser light source, the beat frequencies corresponding to laser upsweeps will be different from the beat frequencies corresponding to the downsweeps as shown in Fig. 13, due to Doppler frequency shifting. In a manufacturing environment vibrational noise is often present due to large motors, vehicles and other noise sources. By averaging the measured signal frequency from an upsweep with an adjacent down sweep, the Doppler noise can be removed from the range measurement. The APDIS Laser Radar is capable of making 2000 Doppler corrected range measurements per second. In addition, the Doppler frequency, and thus the velocity, can also be determined by taking the difference between the two frequencies. For velocities in the direction of the laser beam, the Doppler frequency is given by

$$F_d = (2*velocity)/1550\ nm. \quad (5)$$

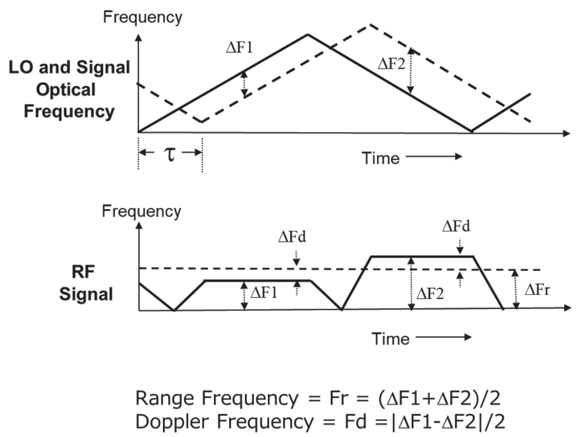

Fig. 13　Effect of moving target.

Prior laser radar systems that performed this Doppler correction did not provide any velocity information. In the APDIS development, this capability was included. Thus, the APDIS system can be used to monitor the vibrational signature of milling machines and other tools in a non-contact manner. Such information can be used to provide feedback to the machining process and to monitor the general health of the machine.

Fig. 14 shows a comparison of the time series of the output of a conventional accelerometer attached to a milling machine and to the APDIS measured acceleration (derived from the measured velocity). The mill was cutting an aluminum block while the measurements were taken.

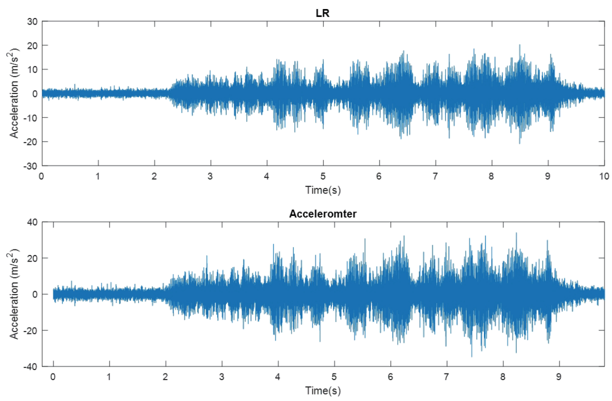

Fig. 14　Comparison of APDIS and conventional accelerometer.

9 Conclusion

The APDIS 4x0 Laser Radar was developed to operate in an industrial factory environment without loss of functionality or precision. It combines an FMCW laser radar with a high-resolution video camera in a stable, confocal configuration to provide for a unique metrology tool. Its sealing against dust and liquids provides for the ability to operate in a harsh manufacturing environment. It is also capable of operating as a laser vibrometer in order to monitor industrial machines.

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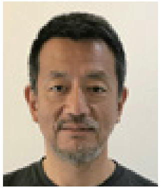
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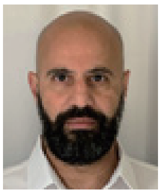
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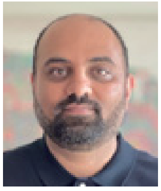
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