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COMPARATIVE ANALYSIS OF INTERFEROMETRIC AND DOPPLER LASER-BASED ACOUSTIC RECONNAISSANCE SYSTEMS AND THE IMPACT OF CORNER REFLECTORS ON THEIR OPERATION

Abstract: This paper presents a comparative analysis of the operation of laser-based acoustic intelligence systems (LAIS) utilizing interferometric (phase-based) and Doppler (frequency-based) detection methods. The physical principles underlying the detection of the target signal, as well as the specific interactions between laser radiation and the surfaces being probed, are examined. Particular attention is given to the influence of corner reflectors on the formation of the received optical signal and their potential use for disrupting the operation of LAIS. The physical rationale for employing such reflectors in various types of systems is discussed, specifically regarding their impact on the ratio between the informative and non-informative components of the received signal. Based on this comparative analysis, the operational characteristics of LAIS under different reflection conditions are identified. The study substantiates the potential use of corner reflectors as a countermeasure against interferometric systems and identifies the need for further research into their effects on Doppler-based LAIS.

Keywords: laser acoustic intelligence systems, corner reflector, retroreflector, interferometric detection, Doppler vibrometry, laser radiation reflection, technical information security, optical countermeasures.

Ensuring the technical protection of information in the modern environment requires a detailed analysis of potential leakage channels for acoustic (speech) information. One such potential technical channel for the leakage of speech information involves the use of laser acoustic intelligence systems (LAIS). These devices enable the detection of micro-vibrations in

structural elements - primarily window glass - caused by acoustic waves originating inside a room [1].

The operational effectiveness of LAIS and the feasibility of establishing an intelligence-gathering link depend significantly on the physical principle used to detect the signal of interest (whether phase-based or frequency-based) and the nature of the interaction between the coherent radiation and the surface being probed. Consequently, it is necessary to investigate how different types of laser reflection - including those involving corner reflectors - affect the performance of interferometric and Doppler-based systems. In this context, the interferometric and Doppler principles should be viewed as distinct approaches to determining surface vibration parameters; these approaches can also be combined within a single optical system.

Interferometric LAIS operate by detecting phase shifts in an optical signal caused by micro-displacements of the surface under observation. In an interferometric optical configuration, a measurement beam is directed toward the target surface (such as a window pane), while a reference beam remains contained within the device itself. When the beams are recombined, interference occurs; consequently, changes in the optical path length of the measurement beam result in variations in the intensity of the received signal. These variations are used to determine phase fluctuations associated with micro-displacements of the surface, which allows for the reconstruction of its vibration parameters [3].

Doppler-based LAIS operate on the basis of the Doppler effect. When laser radiation reflects off a vibrating surface, the frequency of the reflected wave changes in proportion to the surface's velocity along the direction of the radiation's propagation. Measuring the Doppler frequency shift makes it possible to determine the surface's oscillation velocity and reconstruct the acoustic signal. Modern laser Doppler vibrometers may also employ interference-based techniques - specifically heterodyne and homodyne detection—to record these changes [2; 3].

Table 1. Comparative analysis of characteristics

Comparison criterion	Interferometric LAIS	Doppler-type LAIS
Main measurement parameter	Change in the phase of the optical signal associated with surface displacement	Doppler frequency shift proportional to surface velocity
Beam reflection characteristics	Requires a sufficient level of coherent radiation to be returned to the receiver	Can use both specular and diffuse reflection, depending on the system design
Sensitivity to microvibrations	High sensitivity to extremely small surface displacements	High sensitivity to surface vibration velocity
Main limitations	Requirements for optical signal phase stability and interference conditions	Requirements for laser frequency stability, received signal quality, and demodulation accuracy
Susceptibility to interference	Depends on phase fluctuations and additional optical components affecting the interference pattern	Depends on the signal-to-noise ratio, frequency stability, and signal processing characteristics

Corner reflectors (retroreflectors) are optical elements designed to return incident radiation approximately toward its source, regardless of the angle of incidence (within a specific operating range). Their use in technical information security systems is of interest due to their potential to generate an additional component in the optical signal reaching a laser acoustic intelligence receiver (laser microphone).

The nature of this effect depends on the physical operating principle of the laser system. In the case of interferometric laser microphones, the use of corner reflectors is considered a promising approach to optical jamming. Given an appropriate optical system configuration, the radiation reflected by the corner reflector can generate an additional, unmodulated component in the received signal. This component superimposes itself onto the information-carrying signal - which is modulated by the micro-vibrations of window glass - thereby altering the ratio between the signal components and reducing the contrast of the interference pattern. This, in turn, complicates the extraction of the useful acoustic information [1].

For Doppler-based laser microphones, the nature of the impact caused by corner reflectors requires separate investigation. Since such systems determine surface vibration velocity based on the Doppler frequency shift of the reflected radiation, the mere presence of an additional optical signal does not automatically guarantee effective interference. The effectiveness of such an impact depends on the frequency characteristics of the signals, the spatial positioning of the reflector, the parameters of the receiving path, and the specific method of signal processing employed [2].

Thus, the analysis indicates that corner reflectors are of interest as a promising element of passive optical protection against interferometric laser-based acoustic intelligence-gathering systems. With an appropriate optical system configuration, an additional unmodulated component of the reflected radiation can reduce the contrast of the interference pattern, making it more difficult to extract the useful signal.

At the same time, the effectiveness of using such reflectors to counter Doppler-based laser acoustic intelligence systems remains insufficiently studied, as it depends on the specifics of signal reception and interferometric detection, particularly when heterodyne methods are employed. This underscores the need for further theoretical and experimental research.

The selection of technical information protection methods must take into account the specific operating characteristics of the particular type of laser acoustic intelligence system. In addition to passive optical countermeasures, structural measures designed to reduce vibrations in building envelopes - as well as active vibro-acoustic protection utilizing piezoelectric vibration exciters - are of significant importance. An integrated approach combining these measures can enhance the resilience of facilities against the leakage of speech information via acoustic channels.

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