

OPTICAL REMOTE SENSING OF VIBRATIONS

BACKGROUND OF THE INVENTION

1. TECHNICAL FIELD

5 The present invention relates to the field of remotely sensing vibrations, and more particularly, to sensing vibrations remotely using optical means.

2. DISCUSSION OF RELATED ART

10 Various ways were suggested for sensing vibrations, such various mechanical, acoustic and optical methods; the latter including speckle interferometry and laser Doppler vibrometers.

SUMMARY OF THE INVENTION

15 The following is a simplified summary providing an initial understanding of the invention. The summary does not necessarily identify key elements nor limit the scope of the invention, but merely serves as an introduction to the following description.

One aspect of the present invention provides a system comprising: at least two coherent light sources with known phase relations between them, configured to illuminate a target with at least two corresponding spots, an optical unit comprising a mask and configured to focus, onto a sensor, interfered scattered illumination from the spots of the target, passing through the mask, to yield a
20 signal, at least one shifter configured to shift a frequency of at least one of the coherent light sources to provide a carrier frequency in the signal, and a processing unit configured to derive a vibration frequency of the target from the sensor signal with respect to the carrier frequency.

One aspect of the present invention provides a system comprising: at least one coherent light source configured to illuminate a target, an optical unit comprising a mask and configured to focus, onto
25 a sensor, scattered illumination from the target passing through the mask, to yield a signal, at least one mechanical unit configured to move the mask over an aperture of the optical unit at a specified speed to yield a carrier frequency, and a processing unit configured to derive a vibration frequency of the target from an analysis of the sensor signal with respect to the carrier frequency.

30 These, additional, and/or other aspects and/or advantages of the present invention are set forth in the detailed description which follows; possibly inferable from the detailed description; and/or learnable by practice of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of embodiments of the invention and to show how the same may be carried into effect, reference will now be made, purely by way of example, to the accompanying drawings in which like numerals designate corresponding elements or sections throughout.

5 In the accompanying drawings:

Figure 1 is a high level schematic block diagram of a system with a moving mask, according to some embodiments of the invention.

Figures 2A and 2B are high level schematic block diagrams of systems with a stationary mask, according to some embodiments of the invention.

10 **Figure 3** is an exemplary illustration of interference patterns in simulation and in experiment, according to some embodiments of the invention.

Figures 4A-4D are high level block diagrams of illumination sources, according to some embodiments of the invention.

15 **Figure 5** is a high level block diagram of polarized detection, according to some embodiments of the invention

Figure 6 is a high level flowchart illustrating a method, according to some embodiments of the invention.

DETAILED DESCRIPTION OF THE INVENTION

20 In the following description, various aspects of the present invention are described. For purposes of explanation, specific configurations and details are set forth in order to provide a thorough understanding of the present invention. However, it will also be apparent to one skilled in the art that the present invention may be practiced without the specific details presented herein. Furthermore, well known features may have been omitted or simplified in order not to obscure the
25 present invention. With specific reference to the drawings, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of the present invention only, and are presented in the cause of providing what is believed to be the most useful and readily understood description of the principles and conceptual aspects of the invention. In this regard, no attempt is made to show structural details of the invention in more detail than is necessary for a fundamental
30 understanding of the invention, the description taken with the drawings making apparent to those skilled in the art how the several forms of the invention may be embodied in practice.

Before at least one embodiment of the invention is explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of the components set forth in the following description or illustrated in the drawings. The invention is applicable to other embodiments that may be practiced or carried out in various ways as well as to combinations of the disclosed embodiments. Also, it is to be understood that the phraseology and terminology employed herein is for the purpose of description and should not be regarded as limiting.

Unless specifically stated otherwise, as apparent from the following discussions, it is appreciated that throughout the specification discussions utilizing terms such as "processing", "computing", "calculating", "determining", "enhancing" or the like, refer to the action and/or processes of a computer or computing system, or similar electronic computing device, that manipulates and/or transforms data represented as physical, such as electronic, quantities within the computing system's registers and/or memories into other data similarly represented as physical quantities within the computing system's memories, registers or other such information storage, transmission or display devices. Any of the disclosed modules or units may be at least partially implemented by a computer processor.

Reflected signals from targets which are illuminated by a laser are characterized by speckle patterns, which are non-uniform intensity patterns resulting from interference of wavefronts of the reflected laser illumination. When targets are vibrating, the reflected speckle patterns move and, when integrated on a detector, result in a signal with fluctuating intensity due to the small changes of the part of the speckle pattern which is integrated in an aperture associated with the detector. Signal fluctuations may be intensified by a mask set at a pupil plane in front of the detector, which provides more entry and exit lines for speckle with respect to the integration area of the signal.

However, disadvantageously, the amplitude of the detected signal fluctuations depends on the characteristics of the speckle pattern (e.g., dimension and density of speckles) and not on the characteristics of the target vibrations. The inventors have found out that the target vibration amplitude that produces a translation larger than 5-10% of mean speckle size, influences the detected signal frequency rather than its amplitude.

Figure 1 is a high level schematic block diagram of a system **100** with a moving mask **122**, according to some embodiments of the invention. System **100** may be configured to detect vibrating elements **91** in a scene and derive parameters relating to their vibrations. System **100** comprises a coherent light source **95** configured to illuminate a target **91**, typically by a narrow laser beam, and

an optical unit **120** comprising mask **122** and configured to focus, via optical element(s) **125** and onto a sensor **99**, scattered illumination **90** from target **91** passing through mask **122**, to yield a signal **140**.

Starting from a static target **91**, illumination **95** causes a speckle pattern **90A** (illustrated schematically) in scattered radiation **90**, which is collected by optical unit **120** and focused onto detector **99**. Detector or sensor **99** may comprise one or more pixels and may be implemented as a single pixel detector. When target **91** vibrates, speckle pattern **90A** vibrates as well on the aperture of optical unit **120**, resulting in intensity fluctuations on detector **99**, which are termed herein "modulation" of the signal. The modulation is at vibration frequency(ies) of target **91**. A mask **122** at the aperture may be designed or selected to enhance the amplitude of the modulation, depending on the relation between the geometrical parameters of mask **122**, speckle dimensions and vibration amplitude. Therefore, in the prior art, a vibration frequency of target **91** may be derived from the frequencies in the modulation.

In certain embodiments, mask **122** is moved at a specified speed over the aperture. Assuming a static target, speckle pattern **90A** is also static and the motion of mask **122** results in a specified modulation having a specified frequency termed herein the carrier frequency f_c , denoted **131** in **Figure 1**. Once target **91** vibrates as well, and assuming the carrier frequency is much larger than the vibration frequency(ies) of target **91**, f_c is frequency-modulated (FM) by the target vibration frequency (see frequency shift in the frequency domain, denoted by **131A** and illustrated schematically as signal **140** in **Figure 1**). (It is noted that the spectrum is shown schematically in a non-limiting manner and may include larger side lobes, depending on the modulation index.) The vibration frequency(ies) of target **91** may therefore be extracted from the measured modulation by known methods. It is noted that in these embodiments, mask **122** plays a dual role of amplifying the modulation (resulting from the vibrating speckle pattern) and of providing the carrier frequency; and speckle pattern **90A** provides the information about the vibration frequency(ies) of target **91**. System **100** further comprises a mechanical unit **124**, e.g., a chopper, configured to move mask **122** across the aperture of optical unit **120** at a specified speed to yield and provide the carrier frequency f_c . System **100** further comprises a processing unit **150** configured to derive vibration frequency **131A** of target **91** from an analysis of sensor signal **140** with respect to carrier frequency **131**. Advantageously, the vibration intensity may also be estimated by processing unit **150** from signal **140**. Mechanical unit **124** and the carrier frequency f_c may be optimized with respect to required signal amplification and with respect to speckle characteristics

Figures 2A and 2B are high level schematic block diagrams of system **100** with stationary mask **122**, according to some embodiments of the invention. Referring to **Figure 2A**, system **100** may be configured to detect vibrating elements **91** in a scene and derive parameters relating to their vibrations. System **100** may comprise at least two coherent light sources **95** with known phase relations between them, which are configured to illuminate target **91** by at least two corresponding spots **96** (indicated schematically). Coherent light sources **95** are further configured to have correlated phases, e.g., be derived from a single coherent light source. In certain embodiments, coherent light sources **95** are derived from a single laser source **97** split by a splitter **97A** (see examples in **Figures 4A-4D** below). System **100** may further comprise optical unit **120** comprising static mask **122** and configured to focus, onto sensor **99**, interfered scattered illumination from target **91**, passing through mask **122**, to yield signal **140**. Sensor/detector **99** may comprise one or more pixels and may be implemented as a single pixel detector. It is noted that the term vibrations is used in a broad sense to refer to various types of kinetic changes of elements **91**, such as any change (e.g., movements, rotations etc.) that causes a change of the relative phase between radiation reflected from spots **96**. The relative phase is detectable as described herein and used to detect the respective kinetic change.

Two (or more) illumination sources **95**, having correlated phases, are used to illuminate two close areas on target **91** (denoted as spots **96**), so that the scattered radiation therefrom interferes on the aperture of optical unit **120** to provide an interference pattern **92** (shown schematically) which is collected to yield detected signal **140**. Assuming a static target, interference pattern **92** is static, and speckle pattern **90A** is expressed as deformations with respect to a clean interference pattern (see an example in **Figure 3** below). Once target **91** vibrates, interference pattern **92** vibrates as well, resulting in a signal modulation.

In order to provide frequency modulation, carrier frequency f_c **131** may be generated by controlling the relative phase between illumination sources **95** and/or shifting the frequency of one source **95** with respect to another source **95**, to yield carrier frequency $f_c \gg$ target vibration frequency(ies) **131A**. (It is noted that the spectrum is shown schematically in a non-limiting manner and may include larger side lobes, depending on the modulation index.) The modulation, resulting from target vibrations, is turned into a FM modulation of f_c and may be derived by known methods. It is noted that in these embodiments, mask **122** may be selected only to amplify the modulation (resulting from interference pattern **92**), and the speckle pattern is merely a disturbance that deforms interference pattern **92**, as illustrated in **Figure 3** below.

Figure 2B illustrates schematically a somewhat more complex signal spectrum **140** having additional vibration frequency harmonics that may be used for FM demodulation **152** followed by further processing **154** by processing unit, leading to identification of vibration frequency **131A** in analysis results **155** of the vibration frequencies. In some embodiments, additional detector(s) **99A** and/or optical unit(s) **120A** (shown schematically) may be used to derive additional spectra **140A** which may be FM-demodulated **152A** and incorporated in processing **154** and analysis **155**.

The inventors have shown in simulation and experimentally, that changing the distance between spots **96** controls the density of interference pattern **92** which in turn changes the intensity of vibration signal **133** but not the modulation. Therefore, increasing the distance between spots **96** improves the SNR (signal to noise ratio). Moreover, diminishing spot size increases the SNR, but also the sensitivity to atmospheric conditions. The inventors have further shown, both analytically and experimentally that, unlike speckle interferometry, disclosed methods measure translational difference between the spots with the same sensitivity as tilt angles of the surface on which the spots fall. The disclosed methods and systems thus combine the advantages of speckle interferometry and laser Doppler vibrometers to provide improved systems. Any of the distance between spots **96**, spot sizes, parameters of mask **122**, parameters of optical unit **120** and the modulation of illumination sources (i.e., f_c) may be optimized with respect to each other to optimize system performance. In certain embodiments, optical unit **120** may be configured to comprise at least one polarizer configured to further improve the SNR, as explained below.

System **100** may comprise at least one shifter **130** such as at least one frequency shifter **132** and/or at least one phase shifter **134**, configured to shift the frequency of at least one of coherent light sources **95** according to predetermined shifting characteristics, and processing unit **150** may be configured to derive vibration frequency **131A** of target **91** from a relation between sensor signal **140** and the predetermined shifting characteristics. The configuration of shifter(s) **130** to determine carrier frequency f_c is shown schematically in **Figure 2A** by an arrow, near interference pattern **92**. In embodiments, shifter(s) **130** may comprise at least one RF (radiofrequency) shifter **132** configured to shift an illumination frequency of one or more phase-correlated or possibly phase-locked coherent light source(s) **95** by a predetermined RF frequency **131**. The vibration frequency may then be derived from a component **133** in sensor signal **140** at a frequency that is shifted from predetermined RF frequency **131**. In embodiments, shifter(s) **130** may comprise at least one phase shifter **134** configured to shift a phase of one or more coherent light source(s) **95** by a predetermined

phase shift pattern. The vibration frequency may then be derived from a relation between sensor signal **140** and the predetermined phase shift pattern.

Advantageously, with respect to certain embodiments of mechanical unit(s) **124**, system **100** with two or more illumination sources **95** and shifter(s) **130** may comprise fewer or no moving mechanical parts, overcome challenges of designing mask **122** as well as be less sensitive to small speckles. Embodiments illustrated in **Figures 2A** and **2B** provide an interferometric approach to vibrations sensing, with all interferometer paths being outside optical unit **120**, namely being between illumination sources **95**, target **91** and optical unit **120**.

Figure 3 is an exemplary illustration of interference patterns **92** in simulation **92A** and in experiment **92B**, according to some embodiments of the invention. Mask **122** is illustrated schematically as having parallel straight lines, and interference patterns **92** are shown as derived from simulation **92A** and from experiments **92B** in an exemplary manner. Speckle pattern **90A** is transformed through the use of two illumination sources **95** and interference pattern of the respective reflected radiation, into modulated line patterns which are then focused on detector **99** through mask **122**. In the embodiments illustrated in **Figures 2A** and **2B**, speckle pattern **90A** is expressed in the disturbances in interference pattern and do not convey the information concerning the vibrations of the target. Instead of mechanical modulation with the predetermined modulation characteristics, embodiments with interference patterns may use modulation of illumination sources **95** to enable isolation of a signal proportional to the vibration intensity of target **91**, as explained below.

Figures 4A-4D are high level block diagrams of illumination sources **95**, according to some embodiments of the invention. In certain embodiments, multiple illumination sources **95** may be implemented using a single illumination source **97** which is split (by a splitter **97A**) into two or more illumination sources **95A**, **95B** by a beam splitter **97A**, with shifter(s) **130** implemented as one or more phase shifter(s) **134**, acousto-optic deflector(s) (AOD) **136A**, **136B** and/or other optical components. illumination sources **95A**, **95B** may be configured to provide spots **96A**, **96B** with specified characteristics of target **91**. For example, as illustrated in **Figure 4C**, illumination sources **95** may comprise two lasers amplifiers **137A**, **137B** configured to receive the outputs of AODs **136A**, **136B** and be phase-locked with laser seeder **97**. Illumination from lasers amplifiers **137A**, **137B** may then be combined by a combiner **138**, collimated by a collimator **139** and used as illumination sources **95A**, **95B** to provide spots **96A**, **96B**. In an example illustrated in **Figure**

4D, both AODs 136A, 136B may be located on one split channel. Elements from **Figures 4A-4D** may be combined to form additional embodiments.

Figure 5 is a high level block diagram of polarized detection, according to some embodiments of the invention. In certain embodiments, polarizer(s) 98A, 98B may be implemented to reduce speckle noise. Spots 96A, 96B from target 91 create interference pattern 92 which is then split, e.g., by a polarizing beam splitter (PBS) 93 in optical unit 120 into different polarizations by polarizer(s) 98A, 98B which are detected separately on detector 99 and/or on separate detectors 99A, 99B.

Figure 6 is a high level flowchart illustrating a method 200, according to some embodiments of the invention. The method stages may be carried out with respect to system 100 described above, which may optionally be configured to implement method 200. Method 200 may be at least partially implemented by at least one computer processor. Certain embodiments comprise computer program products comprising a computer readable storage medium having computer readable program embodied therewith and configured to carry out of the relevant stages of method 200. Method 200 may comprise stages for producing, preparing and/or using system 100, such as any of the following stages, irrespective of their order.

Method 200 may comprise illuminating a target by at least two phase-correlated coherent light sources to form at least two corresponding spots (stage 210), possibly splitting the at least two coherent light sources from a single illumination source (stage 212) (see e.g., **Figures 4A-4D**).

Method 200 may comprise focusing, onto a sensor and through a mask, interfered scattered illumination from the spots on the target, to yield a signal (stage 225), shifting a frequency and/or a phase of at least one of the coherent light sources to provide a carrier frequency in the signal (stage 230) and deriving a vibration frequency of the target from the sensor signal with respect to the carrier frequency (stage 250), e.g., from a component in the sensor signal at a frequency that is shifted from the carrier frequency (stage 252), as illustrated e.g., in **Figures 2A and 2B** and in the accompanying description.

Method 200 may further comprise optimizing sizes and spacing of the spots, with respect to parameters of the optical unit and the mask (stage 260). Method 200 may further comprise generating the signal with respect to different polarizations of the interfered scattered illumination, thereby detecting, separately, polarization components of the interference pattern to improve the SNR (stage 262). Method 200 may further comprise configuring the mask with respect to an expected interference pattern of the scattered illumination.

In certain embodiments, method **200** may comprise illuminating the target with one (or more) illumination source(s) (stage **210**), focusing, onto the sensor, scattered illumination from the target through the mask, to yield a signal (stage **220**), moving, mechanically, the mask across the aperture, according to predetermined characteristics, to yield a carrier frequency (stage **240**) and deriving a vibration frequency of the target from an analysis of the sensor signal with respect to the carrier frequency (stage **250**) as illustrated e.g., in **Figure 1** and the accompanying description. The mask parameters and movement parameters, as well as illumination and focusing parameters may be optimized with respect to the expected speckle patterns as described above.

In the above description, an embodiment is an example or implementation of the invention. The various appearances of "one embodiment", "an embodiment", "certain embodiments" or "some embodiments" do not necessarily all refer to the same embodiments. Although various features of the invention may be described in the context of a single embodiment, the features may also be provided separately or in any suitable combination. Conversely, although the invention may be described herein in the context of separate embodiments for clarity, the invention may also be implemented in a single embodiment. Certain embodiments of the invention may include features from different embodiments disclosed above, and certain embodiments may incorporate elements from other embodiments disclosed above. The disclosure of elements of the invention in the context of a specific embodiment is not to be taken as limiting their use in the specific embodiment alone. Furthermore, it is to be understood that the invention can be carried out or practiced in various ways and that the invention can be implemented in certain embodiments other than the ones outlined in the description above.

The invention is not limited to those diagrams or to the corresponding descriptions. For example, flow need not move through each illustrated box or state, or in exactly the same order as illustrated and described. Meanings of technical and scientific terms used herein are to be commonly understood as by one of ordinary skill in the art to which the invention belongs, unless otherwise defined. While the invention has been described with respect to a limited number of embodiments, these should not be construed as limitations on the scope of the invention, but rather as exemplifications of some of the preferred embodiments. Other possible variations, modifications, and applications are also within the scope of the invention. Accordingly, the scope of the invention should not be limited by what has thus far been described, but by the appended claims and their legal equivalents.

CLAIMS

1. A system comprising:

at least two coherent light sources configured to illuminate a target with at least two corresponding spots,

an optical unit comprising a mask and configured to focus, onto a sensor, interfered scattered illumination from the spots of the target, passing through the mask, to yield a signal,

wherein the mask is configured to amplify an amplitude of interfered scattered illumination intensity fluctuations on the sensor,

at least one shifter configured to shift a frequency of at least one of the coherent light sources to provide a carrier frequency in the signal, and

a processing unit configured to derive a vibration frequency of the target from the sensor signal with respect to the carrier frequency.

2. The system of claim 1, wherein the at least two coherent light sources have known phase relations between them.

3. The system of claim 1, wherein the at least one shifter is configured to shift a phase of the at least one of the coherent light sources.

4. The system of claim 1, wherein the at least two coherent light sources are split from a single illumination source.

5. The system of claim 1, wherein the optical unit is configured to generate the signal with respect to different polarizations of the interfered scattered illumination.

6. The system of claim 1, wherein the mask is configured with respect to an expected interference pattern of the scattered illumination.

7. A method comprising:

illuminating a target by at least two coherent light sources to form at least two corresponding spots,

focusing, onto a sensor and through a mask, interfered scattered illumination from the spots on the target, to yield a signal, wherein the mask is configured to amplify an amplitude of interfered scattered illumination intensity fluctuations on the sensor,

shifting a frequency of at least one of the coherent light sources to provide a carrier frequency in the signal, and

deriving a vibration frequency of the target from the sensor signal with respect to the carrier frequency.

8. The method of claim 7, wherein the at least two coherent light sources have known phase relations between them.
9. The method of claim 7, wherein the shifting comprises shifting a phase of the at least one of the coherent light sources.
10. The method of claim 7, further comprising splitting the at least two coherent light sources from a single illumination source.
11. The method of claim 7, further comprising generating the signal with respect to different polarizations of the interfered scattered illumination.
12. The method of claim 7, further comprising configuring the mask with respect to an expected interference pattern of the scattered illumination.
13. The method of claim 7, further comprising optimizing sizes and spacing of the spots with respect to mask parameters.