Extrinsic Fabry–Perot Interferometer Fiber-Optic Microphone
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Abstract—In this paper we describe a new fiber-optic microphone developed as a passive acoustic sensor for traffic monitoring and vehicle classification. It is based on a fiber-optic extrinsic Fabry–Perot (FP) microinterferometer coupled to an external membrane for modulating the FP cavity length and a low coherent superluminescent diode as light source. The frequency characteristic as compared with a standard condenser microphone exhibits a sensitivity range of more than 80 dB between 100 Hz and 15 kHz. Initial results are presented demonstrating acoustic monitoring of aircraft via their characteristic noise spectra using downleads of km length.

Index Terms—Acoustic, classification, fiber-optics, interferometer, microphone, sensors.

I. INTRODUCTION

ACOUSTIC detection and classification of traffic has become a topic of increasing interest for future automated traffic management systems. Reliable acoustic classification has been demonstrated with respect to vehicle classes such as light and heavy trucks, passenger cars, and motorcycles [1]. Fiber-optic microinterferometer sensors appear to be particularly well suited to the monitoring of traffic and for vehicle classification due to their extremely high sensitivity, full electromagnetic interference immunity, and the possibility of installation without digging up the roads [2]. No electrical equipment is required at the sensor-head location, even though the sensor itself may be separated from the processing system by several kilometers of downlead fiber. This is particularly true of phase-sensitive interferometric sensor systems based on single mode fiber-optic technology. In contrast to electrical sensors, which require at least two electrical connections for power supply and signal readout, fiber-optic sensors can be designed with a single fiber for optical “supply” and readout. During recent years different concepts of fiber-optic microphones have been described in the literature [3]–[5]. In this paper, we report on a new extrinsic Fabry–Perot interferometer acoustic sensor (EFPI-A) and investigate its use for localized traffic monitoring on airport taxiways with the aim of classification of different classes of aircraft via their individual noise spectra. The fiber optic sensor system is one component of a multisensor system within the experimental surface-movement guidance and control system (ESMGCS) at the Braunschweig airport, Braunschweig, Germany, which permits the test of novel traffic-sensor configurations under realistic environmental conditions [6]. Fig. 1 shows a schematic of the ESMGCS. It displays the location of the fiber-optic sensors (FOS’s) at one of the taxiways as well as the fiber-optic distributed data interface (FDDI, 100 Mbits/s) network which links six sensor stations with the central control room. For use in initial experiments with fiber-optic sensor systems, cables of 800 m length with eight FC-connectorized 1300 nm single-mode fibers are installed between the sensor location, the central control room and the FOS laboratory. For automatic long term measurements, a CCD-camera located in the central control room and connected to a PC with frame grabber and picture processing software observes the taxiway to correlate the monitored sensor signals with a picture of the corresponding vehicle passing the location of the sensors.

After describing the principle of operation of the EFPI-A in the following section, we will discuss (Section III) experimental results, which are obtained in laboratory experiments as well as under realistic environmental conditions, before finishing with a conclusion (Section IV).

II. PRINCIPLE OF OPERATION

Fig. 2 depicts a schematic of the microinterferometer acoustic sensor system (EFPI-A). Details of the sensor head are shown in Fig. 3. The optical microphone is based on an EFPI for transducing the mechanical input (acoustic wave) into phase (ϕ) modulation of the sensing light wave. The light source (superluminescent diode SLD 561 of SUPERLUM Ltd., Moscow, Russia, wavelength λ = 1300 nm, spectral width δλ ≈ 40 nm, spectral ripple <5%, output power from pigtail typically 500 μW) and photodiode for detecting the reflected interference signal are connected to the EFPI-A via a 3 dB directional coupler and an SM fiber-optic downlead. The end section of the single mode downlead fiber and the reflector fiber are glued into precision fiber ferrules which in turn are collinearly adjusted by means of a cylindrical spring, which is fixed in an adapter for FC/PC SM-fiber connectors. A loudspeaker membrane of 4 cm diameter is mechanically coupled to the reflector fiber ferrule to transfer the acoustic pressure variations into the corresponding distance modulation ΔL(t) between the two FP-mirrors via tilting of the ferrule [tilt angle Θ(t)], as indicated in Fig. 3.

For our case of low mirror reflectivity: Rf ≈ R0 ≈ R ≈ 4% (glass–air boundary), the normalized output intensity

\[ i_r = I_r / I_0 \]

(Ir and Io are the interference signal intensities...
Fig. 1. Schematic of the ESMGCS at Braunschweig airport. An FDDI data link connects the sensor stations S1–S6 with the central control room. Eight 800 m SM downleads to the FOS’s end near the intersection of one of the taxiways with the runway. SDF = sensor data fusion, OP = system operator. AVES = avionics evaluation system.

Fig. 2. Fiber-optic microphone EFPI-A. Sensing element connected via SM-downlead to source/receiver unit with spectrum analyzer for classification of noise sources. $L =$ Fabry–Perot cavity length, PD = photodiode-preamplifier unit, SLD = superluminescent diode, ADC = analog-digital-converter.

reflected back from, and the input intensity into the FP cavity, respectively) of the extrinsic Fabry–Perot interferometer may be approximated by the cosinuidal characteristic of two beam interferometers. Including a factor for modeling the fringe contrast reduction by the finite spectral width $\delta \lambda$ of the source, assuming a Gaussian spectral distribution [7], the FP-characteristic is approximated by (1) [2].

$$\psi_r(t) = 2\lambda(1 - \exp\{- (\Phi \delta \lambda / \lambda)^2\} \cos \Phi(t)), \quad (1)$$

$\Phi = \Phi_0 + \Delta \Phi$ is the phase shift experienced by the light wave as it travels through the FP cavity and back, a distance of $2L$. It is the sum of the offset phase $\Phi_0 = 4\pi L / \lambda$ due to the initial cavity length $L$ and the additional phase shift $\Delta \Phi(t)$, caused by the variation in $L$ by $\Delta L$. For a harmonic oscillation of frequency $f_r = \omega_r / 2\pi$, the phase variation $\Phi(t)$ is given by $\Phi(t) = \Phi_0 + \Delta \Phi(t) = \Phi_0 + \Phi_r \sin(\omega_r t + \Phi_{0r})$. In general the nonlinear interferometer characteristic has to be taken into account. The decomposition of (1) into a series of Bessel functions [8] exhibits a further increase of spectral components at integer multiples of the excitation frequency. In our case, however, the vibration induced phase is small compared with the fringe amplitude: $\delta \Phi \ll \pi / 2$, so that higher harmonics can be neglected and the operating point of the interferometer can always be shifted into a steeply sloped region by adjusting the initial value of $L$ and the initial ferrule tilt angle $\Theta$. $L$ is of the order of one wavelength and is usually adjusted such...
that the operating point of the sensor lies in the steepest slope region of one of the first fringes of the periodic interference near the quadrature point \( \Phi_0 = 4\pi L/\lambda \approx (2m + 1)\pi/2, m = 0, 1, 2, \ldots \). Differentiation of the cosinusoidal interferometer characteristic yields for the sensitivity at \( \Phi = \pi/2 \):

\[
\frac{d\delta r}{dL} = \frac{8R\pi}{\lambda}.
\]

For \( \lambda = 1.3 \mu m \) and \( R = 4\% \) we get \( d\delta r/dL \approx 0.8 \mu m^{-1} \).

For a linear response \( \delta \Phi < \pi \) is required over the expected acoustic pressure range. From (2) follows: \( \delta \delta r \ll 4R \). If we choose \( \delta \delta r = 0.1(4R) \) an upper limit of the distance variation is obtained as \( \delta L = 20 \text{ nm} \). With a ferrule diameter \( a = 2.5 \text{ mm} \) the maximum tilt angle of the reflector as induced by the membrane vibration is approximated as \( \delta \Theta = \delta L/a \approx 1 \text{ arcsec} \), corresponding to a membrane movement of \(<0.2 \mu m \).

III. EXPERIMENTAL RESULTS AND DISCUSSION

For quantitative characterization, measurements in an anechoic test chamber were performed with a Brüel-Kjaer type 4134 condenser (1/2") microphone as a reference (frequency independent response between 10 Hz and 15 kHz). Fig. 4 shows a typical transfer characteristic (log of acoustic pressure ratio/dB and phase versus frequency in the range 100 Hz to 15 kHz) of one of the first EFPI-A versions obtained under these controlled conditions. The sensitivity range covers more than 80 dB with significantly reduced values around 3.5, 5.5, and near 7.5 kHz. The normalization of the EFPI-A signal with respect to the B-K was chosen \( =1 \text{ dB} \) at the 94 dB-point \( =1 \text{ Pa} \) for the 4134 at ca. 300 Hz). The phase exhibits a smooth variation as required for a microphone, decreasing by about \( 170\pi/\text{kHz} \).

As an example of a practical application Fig. 5 shows the acoustic spectra obtained with an EFPI-A exposed to the noise of three different aircraft: DO228 and DO328 turboprop aircraft with three and four blade propeller, respectively, and an A400 jet. The aircraft were on the ground in front of the hangar during the recording of the noise. Data were sampled with 12.5 kHz and FFT’s are performed on 16384 data points. An 11 point moving average filtering was then applied to the FFT’s in order to enhance the significant spectral components. Reduced response is observed in the 3 and 5 kHz range for all three spectra in agreement with the measured sensitivity reduction of Fig. 4. As expected from the qualitative interpretation of the different noise sources, the spectra clearly discriminate between the two turboprop aircraft with increased spectral contributions in the low frequency regime and the jet with dominant lines of the jet engine around 4.1 and 5.2 kHz. However even the weak differences between the three and four blade propeller aircraft are clearly resolved with the optical microphone in the low frequency range \( <500 \text{ Hz} \). The spectra compare reasonably well with those obtained with a conventional microphone which also exhibits an amplitude minimum at 5 kHz. Initial tests for automatic classification were performed using a commercial spectrum analyzer/classifier based on a neural network software (produced by MEDAV GmbH). The results based on continuous evaluation of 2 s time segments of the recording exhibit reliable discrimination between all three aircraft.

As an example for a test under realistic environmental conditions, Fig. 6(a) and (b) show the results of a measurement with an EFPI-A at the end of the 800 m single mode fiber downlead. The CCD-camera frame-grabber picture shows an aircraft waiting at the stopbar with engine running before entering the runway for takeoff. The sensor is mounted on the concrete base of a position lamp in about 2 m distance from the edge of the taxiway [location indicated by arrow in Fig. 6(a)]. The frequency spectrum of the aircraft noise in Fig. 6(b) is calculated from a 6 s time series sampled at 20 kHz acquisition rate. The spectral peaks can be attributed to higher harmonics of propeller and piston engine noise. The large peak at about 900 Hz is not characteristic of the aircraft and probably due to vibrations of the body of the aircraft. Typical values of the propeller noise frequency are \((\text{sub-})\text{harmonics of} \ B \times N \approx 2 \times 30 \text{ Hz} \) = 100 Hz, with propeller blade number \( B \) and engine rotation rate \( N \). The results obtained for the three different aircraft classes (jet, turboprop, and propeller with piston engine) prove the usefulness of this new and completely passive optical sensor for automatic acoustic classification of the type of vehicle passing the sensor location. The respective EFPI-A has been in operation and transmitted audio signals to the remote readout unit in the laboratory for more than half a year in 1996 (with one interruption due to dirt in an FC-connector) until late December, when it was replaced by a new sensor.
Fig. 4. Typical transfer characteristic of one of the first versions of the EFPI-A microphone obtained with Brüel-Kjaer type 4134 reference microphone in anechoic test chamber. Upper graph: relative magnitude (vertical axis: magnitude of complex FFT, logarithmic 10 dB/div); lower graph: phase (500°/div) versus frequency: 0.1–15 kHz, linear scale.

Fig. 5. Acoustic spectra (FFT, 11 point MA filtering) obtained with an EFPI-A exposed to the noise of three different aircraft. From top to bottom: A400 jet, DO328 and DO228 turboprop aircraft with four and three blade propeller, respectively. Both axes logarithmic scale.

IV. CONCLUSION

A new microinterferometer acoustic sensor is investigated as a possible element of a fiber-optic based sensor system for ground traffic monitoring in an ESMGCS. It is based on an EFPI coupled to a membrane for transferring the acoustic pressure induced phase modulation of the sensing light wave into intensity variations of the interference signal. Laboratory experiments as well as first experiments with EFPI-A microphones under realistic environmental conditions yield promising results. The performance of the first versions of

Fig. 6. (a) CCD-camera picture of an aircraft waiting at the stopbar to the runway entrance. Optical microphone position indicated by arrow. (b) FFT of the EFPI-A signal (6 s time series) taken at 20 kHz data rate.
the optical microphone proves the EFPI-A sufficient for discriminating noise spectra of different aircraft types. Automatic classification of aircraft noise spectra appears possible by evaluating the characteristic frequency spectra, which are obtained using fiber-optic microphones connected to the readout electronics via km of single mode fiber.

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REFERENCES

Norbert Fürstenau studied physics at the Universities of Braunschweig, Darmstadt, and Frankfurt, all in Germany. He received the Diplom-Physiker degree in physics from the Institute of Nuclear Physics of the Darmstadt Technical University in 1977. He was a Research Assistant at the Institute of Biophysics at Frankfurt University. He received the Ph.D. degree in the field of laser induced evaporation and mass spectrometry of molecular clusters. From 1981 to 1984, he was with the Institute of Flight Guidance of the German Aerospace Center (DLR) in Braunschweig. He worked on mechanical and laser and fiber-optic gyros for inertial navigation. Since 1984, his research has been on fiber optic interferometric sensors for aerospace applications. Currently, he is head of the Photonic Sensors Group, with interferometric sensors for mechanical quantities as his main research area. He has more than 50 publications and ten patents in the fields of mass spectrometry, molecular clusters, gyro testing, fiber-optic sensors, and optical bistability.

H. Horack, photograph and biography not available at the time of publication.

Walter Schmidt was born in Vienenburg, Germany, in 1956. He received the diploma degree in electronics from the Institute of Control Engineering of the Technical University of Braunschweig, Braunschweig, Germany, in 1987.

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