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OPTICAL PROBE MICROPHONE

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INTRODUCTION

An optical probe microphone is under development for the precise measurement of the pressure waveform in a narrow sound field such as the human glottis. The cross sectional area of the vocal tract changes during speech whilst the glottis is only about 1000 mm^3 in volume and the minimum cross section of the tract reduces to less than 80 mm^2 when a vowel is uttered. If the pressure waveform is to be recorded successfully without interference, the probe microphone must not be more than a few tens of mm^3 in volume, so that its effect on speech is negligible.

In such a small microphone, displacement of the receiving diaphragm caused by the pressure wave is too small to be detected by conventional electrostatic means. If a thin disk clampted at the circumference is subjected on one side to a uniform pressure wave $p=F\sin(2\pi ft)$, and to static pressure on the other, the displacement $D(f)$ of the sensor is given by:

$$D(f)=[3(1-\sigma^2)a^4/(128Eh^3)]F=KF \tag{1}$$

where, a=radius, h=thickness, E=Young's modulus, σ=Poisson's ratio and K=a constant of the disk. K is proportional to a^4 and diminishes rapidly as a is reduced. For example, a mica foil disk of 1 mm radius and 15µm thickness has a K as small as 0.53 nm/Pa. The author has proposed an opto-electronic method of making a very small probe-microphone which uses coherent light and an optical fibre [1]. The diaphragm is combined the end of an optical fibre to form a Fabry-Perot cavity. Pressure waveforms in the glottis cause the diaphragm to vibrate and this alters the Fabry-Perot cavity length. Vibration of the diaphragm is measured by optical interference methods.

A pilot model, constructed to illustrate the feasibility of this proposal, has shown high sensitivity but there are two outstanding problems to be solved before it can be implemented practically. Both problems result from the interference measuring technique employed which causes the optical resonant characteristic of the cavity R(d) to vary periodically and limits the available linear range, efforts for their improvements have been continued. In the present paper, improvements achieved on both linearity and stability are described.

PRINCIPLES AND THEORETICAL ANALYSIS

Coherent light is launched into the cavity and interfers with light reflected back by the diaphragm to give a fringe pattern which depends on the diaphragm location or displacement, the amplitude reflectance of the cavity surfaces and wavelength of the light source.

The intensity of the light reflected back from the cavity into the fibre is proportional to the reflectance R(d) given by [1]:

$$R(d)=[r_1^2+r_2^2-2r_1r_2\cos(4\pi nd/\lambda)]/[1-2r_1r_2\cos(4\pi nd/\lambda)+(r_1r_2)^2] \quad (2)$$

where, n is the refractive index of air and r_i is the amplitude reflectance of the surface i for the light travelling from air to the surface i. R(d) is a periodic function of period 0.5λ with respect to the cavity length d.

If the output from the Fabry-Perot cavity is detected by a photo detector, then the sensitivity of the system is given by equations (3) and (4).

$$s=A(\ell o)\cdot\alpha \ (v/Pa) \quad (3)$$

$$A(\ell o)=t\cdot Rl\cdot G\cdot Io\cdot R'(\ell o), \ (v/m) \quad (4)$$

where, α (m/Pa) is the change in cavity length d per unit pressure, t is the equivalent transmittance of the whole optical system, Rl is the load resistance of the photo detector, G is the sensitivity of the photo detector at wavelength λ, Io is the power intensity of the light source, R' is the first derivative of R(d) and ℓo is the equilibrium position (EP) of the diaphragm.

If the photo detector shot noise and the thermal noise of its load dominate the system noise, the minimum detectable sound pressure Fmin is given by:

$$Fmin=[((NEP\cdot Sa)^2+4kT)B]^{\frac{1}{2}}/[t\alpha GIoR'(\ell o)] \quad (5)$$

where, B (Hz) is the band width of the system, NEP is the noise equivalent power of the photo detector (equal to the input power when the signal to noise ratio of the detector output is unity), Sa is the radiant sensitivity, k is Boltzmann's constant and T is temperature.

PILOT MODEL

Figure 1 shows a block diagram of the pilot model [2]. Light from a power stabilized single mode linearly polarized He-Ne laser is split into two beams by beam splitter BS_1. One beam is used as a reference and detected by photo detector PM_1. The second passes through polarizer P, a quarter wave plate QWP,

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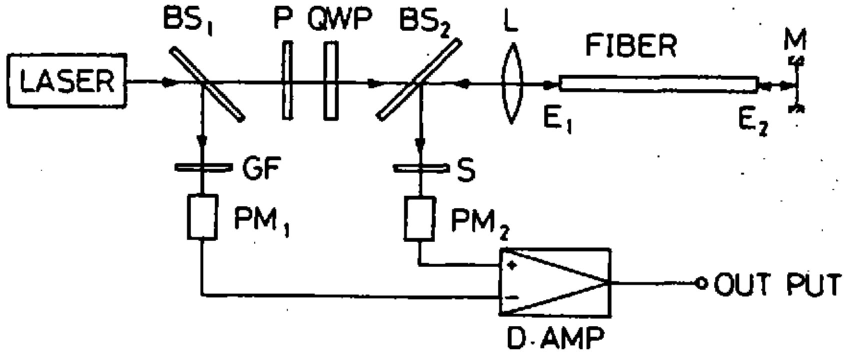

Fig. 1 Structure of the experimental probe microphone

beam splitter BS_2 and is launched into an optical fibre at E_1 by lens L. Exit light from the fibre illuminates the Fabry-Perot cavity E_2-M: reflected light is relaunched into the fibre at E_2, split off at beam splitter BS_2 and detected by photo detector PM_2.

The prototype has been used successfully to record the pressure waveforms in the vocal tract during speech and its sensitivity has been measured as -42 dB (rel. 1 v/Pa = 0 dB) confirming the validity of equations (3) and (4).

There are, however, two outstanding problems to be solved before the device can be implemented practically. One is the poor repeatability and the poor stability of EP of the diaphragm and the second is the restricted linear range of the system.

Both the cavity length and the equilibrium position EP vary with temperature which make it impossible to locate precisely the equilibrium position.

The linearity of such a microphone is largely determined by the amplitude reflectance of the Fabry-Perot surfaces which is a function of the thickness of the aluminium thin films evaporated onto these surfaces to adjust reflectance. The effect of the reflectance is analyzed in the paper.

Temperature dependence of the equilibrium position (EP) and the Fabry-Perot cavity length is the principle reason for instability of the microphone characteristics. It was found to be impossible to fix both the equilibrium position of the diaphragm and the Fabry-Perot cavity length at a precise location in the pilot model.

PERFORMANCE OF IMPROVED MODEL

Linearity

The linear range may be expanded as much as 0.4λ if both r_i and t_i are controlled by carefully monitoring the thicknesses of the thin metallic films deposited as reflective surfaces. If the surfaces of a cavity are made from thin metallic films, rather than from dielectric, the conductivity of the film induces an optical intensity of the transmitted light.

Fig. 2(a) shows the cross-section of a five layer cavity system. Reflectance of the cavity system R(d,λ) is given by:

$$R\,(d,\lambda) = \left| r^*_{1,11} + \frac{r^*_{11,111}t^*_{1,11}t^*_{11,111}\exp(j4\pi n_{11}d/\lambda)}{1-r^*_{11,111}r^*_{11,1}\exp(j4\pi n_{11}d/\lambda)} \right|^2 \qquad (6)$$

where r^*_{ij} and t^*_{ij} represent the overall amplitude reflectance and transmittance for light traversing a multi-layered system from layer i to layer j, where the first and the last layers are identified by subscripts i and j. In the three layered system of Fig. 2(b), r^*_{31} and t^*_{31} are given by:

$$r^*_{31}=r_{32}+t_{32}t_{23}r_{23}\exp(j4\pi n_2h/\lambda)/[1-r_{21}r_{23}\exp(j4\pi n_2h/\lambda)] \qquad (7)$$

$$t^*_{31}=t_{32}t_{21}\exp(j2\pi n_2h/\lambda)/[1-r_{21}r_{23}\exp(j4\pi n_2h/\lambda)] \qquad (8)$$

where r_{ij} and t_{ij} are the reflectance and transmittance of a two layered system of media i and j with refractive indexes n_i and n_j. r_{ij} and t_{ij} are given by:

$$r_{ij}=(n_j-n_i)/(n_i+n_j), \qquad (9)$$

$$t_{ij}=2n_i/(n_i+n_j). \qquad (10)$$

Figure 3 shows calculated value of R for n_1=1,45, n_{11} = 1.0, n_M=1.44+j5.23, h_1=5nm and h_2=20nm. The characteristic has an inverse triangular asymmetric profile with a linear range of approximately 0.4λ; the best achieved with a cavity with dielectric surfaces was 0.1λ. Equation (6) has been confirmed experimentally [3]. A computer programme has been developed to determine the film thicknesses which give the optimum linearity and the highest gain.

Stability

Instability may be reduced by controlling EP using a feed back loop. A null balance system has been devised in which the displacement of the diaphragm due to the combination of the applied pressure wave and thermal expansion of the holder is offset by an electromagnetic restoring force; the feedback signal to the restoring mechanism is then a measure of the pressure wave. Figure 4 is a schematic diagram showing the principle of the force-balance optical probe microphone. The sensing part of the microphone consists of a Fabry-Perot cavity one surface of which is formed by the microphone diaphragm. The axial position of the diaphragm is maintained constant by a feedback mechanism. A fixed proportion of the output signal is fed back and used to maintain the overall cavity reflectance at a constant value. Providing a linear operation of the driving system, the feed back signal is proportional to the sound pressure over the entire range of the diaphragm.

Figure 5 shows the prototype microphone probe consisting of the diaphragm and the Fabry-Perot cavity. A commercially available dynamic loudspeaker is used as the diaphragm to the centre of which is attached a small mirror. The second surface of the Fabry-Perot cavity is formed by the polished end of a step-index single-mode fibre (Fujikura SM 10/125, 10) held parallel to the mirror in a holder ventilated by small holes. The feed back singal activates the voice coil of the speaker to complete the feed back. Light is launched into the input fibre from a 780 nm, 3 mW laser diode (Mitsubishi NL 4402) the output power and wavelength of which is stabilized, the return signal is detected by a PIN photodiode (NEC NDL 2208). The detected output is passed through a low pass filter (cutoff frequency 5 kHz, -80 dB/dec.), and compared with a stabilized reference. The difference forms an error signal which is amplified and drives the voice coil of the speaker to adjust the axial position of the diaphragm. Proportional control is used to keep the output from the probe constant for all values of the measurand.

Figure 6 shows the frequency response of the microphone. Feedback improves not only the stability of the cavity but also the uneven frequency response of the diaphragm. The new probe has shown stable operation during runs of more than ten minutes.

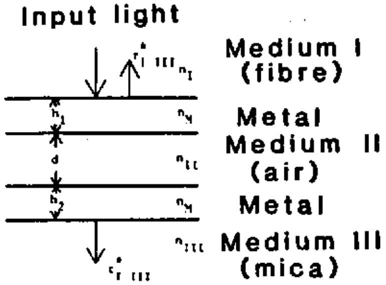

Fig. 2(a) Amplitude reflectance and transmittance of a five layered system.

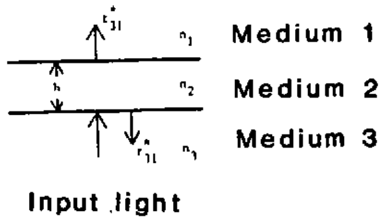

Fig. 2(b) Three layered system.

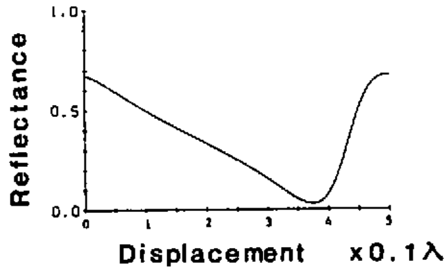

Fig. 3 Reflectance with a wide linear range.

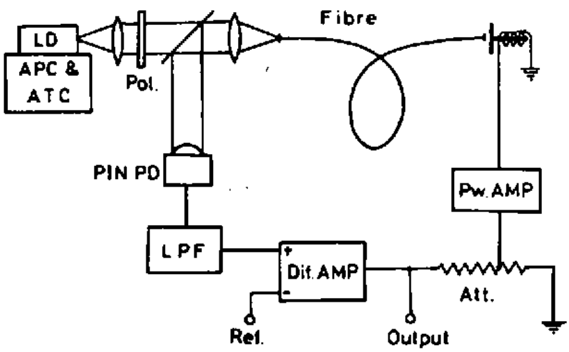

Fig. 4 Schematics of feedback loop.

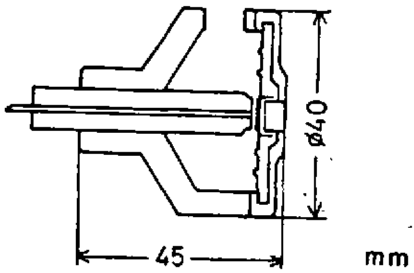

Fig. 5 Sensing part of the prototype microphone probe.

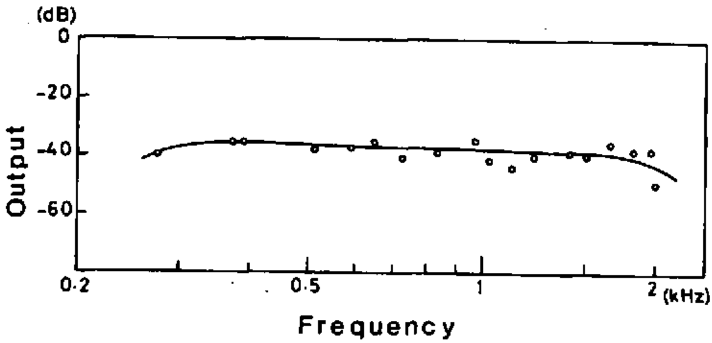

Fig. 6 Frequency response of microphone.

DISCUSSION AND CONCLUSIONS

The two residual problems outstanding from the initial prototype optical probe microphone have been reduced in magnitude by controlling the amplitude reflectances of the Fabry-Perot surfaces and by using a null-balance system to measure the pressure acting on the diaphragm. The latter improves both the stability of the cavity and the frequency response of the diaphragm. The feedback mechanism, however, requires an active element which is undesirable from a safety point of view when probing the human body in vivo. Equation (6) shows that $R(d,\lambda)$ is a function of both d and λ, i.e. d/λ. It may therefore be possible to use wavelength as the variable to keep the probe output constant. This method retains most of the merits of the null-balance system but in addition is entirely passive. A further prototype model based on this principle is under construction.

REFERENCES

[1] R. Ohba, T. Umetsu and N. Mikami: Optical Fibre Probe Microphone, Trans. IECE of Japan, Vol. J64-C, 2, 137/144 (1981).

[2] R. Ohba: Optical Probe for Narrow Sound Fields, ACTA IMEKO 1982, North-Holland, Amsterdam, Vol. 2, pp. 453/462 (1983).

[3] R. Ohba and H. Inoue: Optical Probe Microphone Improved in the Linearity, ICO-13 Conf. Digest, Sapporo 1984, pp. 496/497, (1984).