I. INTRODUCTION

MACHINE maintenance can be broadly categorised into two types - Reactive and Preventive maintenance(1). While the former indicates that action is only taken when the parts in question malfunction or experience damage, the latter is where periodic restoration is done. Each method has its own advantages - while the first helps in cutting costs at least during the lifetime of the machine, the second can help increase its lifetime itself. This is where vibration sensing and condition based monitoring can play a vital role in bringing the best of both worlds to the table. Condition based monitoring involves the continuous monitoring of various machine health parameters like vibration, temperature, sound etc. And under the vibration pattern of the machine surface is known to provide the earliest signs of incipient faults.(2)

In our project, we have developed a non-contact vibration sensor with the help of low-cost plastic optical fibres and off-the-shelf components. Its non-contact feature allows us to potentially bypass mounting constraints and perturbations to the machines vibrations due to the sensor itself. This report outlines the working of the sensor, its experimental setup and our results.

II. SETUP AND WORKING PRINCIPLE

The setup consists of an LED whose light is incident directly upon the surface of a vibrating membrane. The reflected light is captured by a plastic optic fibre and is processed by a photodiode receiver circuit.

Our choice of components are explained Section III.

Theoretical Analysis

The discussion in this section follows the work done in (3).

The ratio of the power received at the photodiode circuit to the ratio of the power transmitted by the circuit containing the LED depends on several factors, including the plastic optic fibres used and more importantly, the distance of the vibrating membrane from a fixed position. The variation of this power as a function of distance of the membrane from the POF (d) is given in Figure 1. If d is small, the power can be approximated as a linear function of the distance:

\[
\frac{P_r(d)}{P_t} \approx R_0 + R_1(d - d_0)
\]

where \(d_0\) is mean value of d. Rewriting d as \(d = d_0 + s(t)\):

\[
\frac{P_r(d)}{P_t} = R_0 + R_1s(t)
\]

and hence the received signal \(v_R(t)\) is

\[
v_R(t) = A_v L_0(t)(R_0 + R_1s(t))
\]

Where A incorporates factors like amplifier gain, POF attenuation, membrane reflectivity etc. and \(v_L\) is the LED drive voltage.

On choosing the driving signal of the LED as a combination of DC and an AC sinusoid, that is

\[
v_L = V_0 + V_1 \sin(\omega LED t) \tag{1}
\]

and s(t) to be purely sinusoidal such that

\[
s(t) = A_v \sin(\omega_{mem} t)
\]

\(v_R(t)\) can be written as

\[
v_R(t) = A V_0 R_0 + A V_0 A_v \sin(\omega_{mem} t) + A R_0 V_1 \sin(\omega LED t) + (A/2) R_1 A_v V_1 \cos((\omega_{LED} - \omega_{mem}) t)
\]

\[
+ (A/2) R_1 A_v V_1 \cos((\omega_{LED} + \omega_{mem}) t) \tag{2}
\]

which corresponds to five peaks at \(\omega = 0, \omega_{mem}, \omega_{LED}, \omega_{LED} - \omega_{mem}\) and \(\omega_{LED} + \omega_{mem}\). The peaks of interest are at \(\omega_{LED} - \omega_{mem}\) and \(\omega_{LED} + \omega_{mem}\) because they are proportional to the vibration amplitude.

III. EXPERIMENTAL ASSEMBLY

The block diagram of the whole test setup is shown below. We used a reflecting membrane vibrating at a monotone frequency to characterise the sensor. The membrane i.e aluminium foil was wrapped around a speaker which played a monotone sound.
A. Transmitter

As shown in the Figure 3, the transmitter side has a super bright red led (3W) fixed on a table. This LED light is reflected by the vibrating aluminium foil. This speaker was kept on a different table than the transmitter and receiver. The following measures were taken to minimise vibration coupling between the two tables:

- The diaphragm of the speaker was placed orthogonal to floor (which is the medium that couples vibrations between the tables)
- The table for the LED/POF enclosure was very big in comparison to the enclosure ensuring very tiny amplitude of oscillation locally around the enclosure.

The LED was modulated by a function generator (as per Equation 1 and the Bluetooth speaker was driven using a mobile tone generator app. These vibrations were sensed by POF in terms of the light reflected by the foil. The super bright LED was modulated at (frequency).

B. Receiver

The light reflected back from the vibrating foil is sensed by a Plastic Optical Fibre (POF) which is attached near the Super Bright LED. Plastic optical fibers were chosen over conventional glass optical fibres because of their low cost, ease of coupling because of their large numerical aperture and flexibility (allows them to be inherently shock/vibration proof)(3). Continuing with the setup, on the other end of the POF, there is a photodiode (SFH203) which converts this sensed light into current. With the help of a transimpedance amplifier the current is amplified and converted to voltage. This converted voltage is sampled by an NI 6008 DAQ and processed in LabVIEW.

The LED was chosen to be red because the POF has been optimised for minimum attenuation at red and even the photodiode has acceptable sensitivity at the 650nm red wavelength.

IV. SIGNAL PROCESSING

A LabVIEW program (Refer: Figure 5) has been written to initialise the DAQ board and to process the data collected by it. The output of the program is the FFT of the input data after averaging over 20 sets of 10 secs of data. One such FFT has been shown in Figure 6.

In totality, five peaks are expected as discussed in Section II. These peaks have been shown in the Figure 6.

We want to make sure that these peaks that we are observing actually correspond to the vibration of the membrane. To do that, a consistency check was performed on the $\omega_{\text{LED}} - \omega_{\text{mem}}$ peak. With the speaker frequency fixed, the LED modulation frequency was changed by ±2 Hz. Corresponding to this change we expect the peak in the FFT to shift by ±2 Hz as well. This has accordingly been observed as shown in Figure 7.

While there are indeed 5 peaks as expected, we want to be able to reliably extract the amplitude of vibration as well. Given that we can’t measure the exact physical amplitude of vibration without attaching something like an accelerometer,
A linear increase in phone volume is a logarithmic increase in amplitude. Hence, linearity in the plot shows that peak height varies linearly with volume just as expected. Therefore the FFT peak height is indeed a measure of the vibration amplitude.

Alongside verification of this proof-of-concept, a plot of the transfer function over a range of frequencies is shown in Figure 9. The y-axis range is the same as that of an FFT seen in Figure 7.

V. INFERENCES AND CONCLUSIONS

The sensor can indeed be used to sense vibrations as demonstrated by Figures 7 and 8.

However, to verify whether the correct vibration amplitude has been measured, we need to cross-check our result with data from an accelerometer placed on the membrane.

There’s also a lot of noise in the data including unwanted harmonics from ambient light and the signal conditioning pipeline (verified by plotting the FFT with no speaker vibration and LED turned off). This is affecting the SNR of the sensor.

VI. FUTURE WORK

- Verify the accuracy of the measurement by suitable comparison with an accelerometer.
- Improve SNR of the output by using focussing apparatus to concentrate the diffusive LED light.
- Automate Peak Detection.

VII. CONTRIBUTIONS

- Hrishikesh Iyer: Building and improving the receiver circuit, designing, drafting and 3D printing housings for
various components (not used finally), loudspeaker circuit to drive a wired speaker (not used finally), experimental assembly setup, LabVIEW pipeline and data acquisition, testing and characterisation, presentation, report.

- Ruchira Nandeshwar: Building and testing the receiver circuit, design of POF housing (not used finally), building a laser modulation circuit (not used finally), experimental assembly setup, presentation report.
- Mekhala Paranjpe: Building the receiver circuit, design of POF housing (not used finally), loudspeaker circuit to drive a wired speaker (not used finally), plotting of FFT of a timeseries (not used finally), presentation, report.

REFERENCES