Measurement 96 (2017) 52–57

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Mobile device-based shaft speed estimation

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ARTICLE INFO

Article history:
Received 23 March 2016
Received in revised form 1 August 2016
Accepted 4 October 2016
Available online 10 October 2016

Keywords:
Shaft rotational speed
Condition monitoring
Hilbert transform
Pearson correlation coefficient
Mobile phone

ABSTRACT

One of the fundamental parameters that needs to be fed into a rotating machinery condition monitoring system is the rotational speed of shaft operating in the system. This parameter is essential in order to derive other characteristic frequencies that may contain some valuable diagnostic information. There are many dedicated hardware elements used in determining the rotational speed of elements however the installation of them usually translates to additional cost of the entire condition monitoring scheme, especially if retrofitting is concerned, and may not always be financially viable due to potentially long payback period on the investment, as in the case of e.g. LV induction motors. This text investigates the possibility of assessing the rotational speed of a shaft based solely on the capabilities of a standard, off-the-shelf mobile phone. The results presented in this text seem to indicate that with an appropriate signal processing approach, it is possible to ascertain the speed of the rotating element using a tool available nowadays to virtually all service technicians.

1. Introduction

In majority of occasions the rotation of the shaft is the main source of power to the system, and so almost all characteristic frequencies that can be observed in the spectrum are somehow related to the shaft rotational speed. From the machinery condition monitoring viewpoint monitoring these components constitutes the basis for many dedicated algorithms, developed to inform on the developing faulty condition of the machine.

Very often the shaft rotational speed is determined by means of a dedicated hardware e.g. tachometers, encoders or laser light readings installed in the close proximity to the rotating element or coupled with the element directly. Information provided by these tools give an easy to interpret and utilize indication of the angular position of the shaft or its rotational speed. The disadvantage of such an approach is that additional instrumentation is required which adds to the complexity of the measurement set-up and increases the cost of performing reliable condition monitoring. Also the installation of such devices needs to be very precise and so it is quite common that limited accessibility to the typically covered shafts may make the appropriate installation of these devices virtually impossible without having to bring the entire system to a full stop. This limitation motivated research into possibilities of determining the rotational speed of the shafts in an indirect, sensor less way e.g. without the use of any dedicated sensors, purely based on signals from sensors which are required to perform other diagnostic exercises anyway (e.g. vibration sensors).

One of the first successful attempts at determining the information about the shaft rotational speed from vibration signals was proposed in [1] where the approach was to phase demodulate of one harmonic of the mesh frequency of a gear vibration signal in order to determine the instantaneous frequency of the given frequency component which by nature is phase coupled with the shaft rotational speed. This development paved the way for further research which was aimed at achieving the same principal goal by different means. In [2–4] the task was achieved by estimating the instantaneous frequency of a single spectral component of determined through a time–frequency representation or other tracking techniques. Combet et al. [5] proposed assessing the relative speed gaps between two stationary signals by means of the Scale transform, which was later extended to a more robust short time Scale transform by Combet and Zimroz duet in [6,7]. The contribution of authors in [8–11] concentrate around time-frequency based approaches although many other tactics have been developed including harmonic decomposition based in [12], model based approaches [13,14] or exploiting the properties of wavelets [15] just to mention a few. A much more comprehensive overview can be found in many of the recent review papers on the subject e.g. [16]. At the same time it should be noted that the use of vibration sensors may not always be financially viable when performing

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http://dx.doi.org/10.1016/j.measurement.2016.10.005
0263-2241/© 2016 Published by Elsevier Ltd.

condition monitoring of non-critical machinery. Recently Rzeszucinski et al. [17] and Orman et al. [18] suggested a cost effective condition monitoring approach for performing the health assessment of rolling element bearings for LV motors based on acoustic signals recorded by a regular mobile phone. In these papers the shaft rotational speed has been measured by a high-end encoder which limited the flexibility of the entire approach. It might therefore be desirable to be able to assess the shaft rotational speed without the need of using peripheral hardware, instead incorporating the capabilities of the mobile phone itself.

The microphones embedded in the modern mobile devices may be used not only to register the human speech but also to record any acoustic signals in the audible range. Relatively high sampling frequency of the audio channel(s) (44.1 kHz) makes the range of potential applications very broad and, specific to this application, allows for high quality representation of signals typically related to the functioning of LV motors. Dedicated mobile phone applications allow for the process of recording the ambient sounds to be robust and time efficient. In the context of rotating machinery the mobile phone may be used to record the acoustic signals generated by vibrating elements and so the direct contact between the machinery and the acoustic-to-electric transducer is not required.

In this paper, the feasibility of using acoustic signals generated as well as recorded by standard mobile phones for determination of rotational speed of a shaft is presented. The measurements were taken with a mobile phone equipped with a dedicated application specifically for the purpose of simultaneously generating and recording the acoustic signals. These operations are performed by the embedded mobile phone loudspeaker and the embedded mobile phone microphone respectively. With the inherent limitations of the standard microphones embedded in mobile phones some signal processing techniques were used to allow for a reliable speed estimation. The results contained in this paper show that the capabilities provided by modern mobile phones make it possible to assess the rotational speed of the shaft based purely on acoustic signal analysis.

2. Methodology

2.1. Background

In theory the shaft rotational speed should be the dominating frequency within the acoustic signal originating from vibration machinery. Such an assumption is sensible provided that the mobile phone is recording in the closest vicinity to the rotating shaft. However in industrial applications the shaft speed-related components are often masked by much more noisy elements e.g. gearboxes, fans or compressors. Another factor that has to be taken into account is that the frequency response function of the embedded microphone is designed to mostly focus on transmitting human voice. This often translates to a frequency band which guarantees undisturbed transmission of information on one hand, yet limits the amount of data that needs to be transmitted to an acceptable minimum. From the telecommunication point of view human voice rarely carries important information below 200 Hz and so this is what the mobile audio devices are designed to deal with. This, in turn, means that all the frequencies below 200 Hz are virtually invisible in the signal and finding the component related to the shaft rotational speed might be considerably more difficult that in the case of e.g. an industrial accelerometer.

2.2. Proposed approach

One of the techniques that might be used to overcome these limitations and which is very broadly used nowadays for approaching similar type of situation, however for completely different applications, is modulation. In the field of telecommunications modulation is used to shift the information-carrying signal into a frequency band that is intended for transmission [19]. For example for mobile communication services modulation is used to shift the speech signal, defined in the range 300–3100 Hz, onto the mobile communication frequency e.g. in the ranges between 800 and 900 MHz [20]. For the purpose of the investigation described in this text the amplitude modulation approach has been used to shift the acoustic signal generated by rotating shaft into a higher frequency band where the influence of other components of the system is expected to be greatly diminished. The idea is to use the imperfections inherently introduced in virtually any shaft line assembly. As a shaft rotates it moves slightly (in the range of tenths of millimeter) around its axial plane. As an artificially generated tone generated by the loudspeaker of the mobile phone is projected onto the surface of the rotating shaft some portions of the generated waveform will be reflected back towards the microphone of the mobile phone. The misalignment, as well as other inherent shaft imperfections e.g. unbalance or bent shaft, result in generation of vibrations at the fundamental shaft rotational speed [21]. When a waveform of frequency which is considerably higher than the rotational speed of the shaft gets reflected off the surface of the shaft it will be amplitude modulated at the rotational speed of the shaft due to different amounts of energy arriving at the microphone of the mobile phone. Since the mobile phone is simultaneously generating the carrier signal and recording the reflections of the surface of the shaft it is expected that the recorded signal will contain the carrier frequency component and sidebands around it, spaced at the shaft rotational speed, indicative of the amplitude modulation of the signal. A person skilled in the art of digital signal processing may find a number of ways of automatically extracting this modulation frequency from the series of sidebands around the carrier frequency. An approach adopted in this text includes calculating the correlation coefficient between the band-pass filtered acoustic signal and artificially generated sinusoids of different frequencies. The first step involves band pass filtering the signal around the carrier frequency. The filter is centered at the known carrier frequency, and its width is twice the expected, estimated rotational speed of the shaft to each side of the carrier frequency. Even though the exact range of the speeds does not have to be exactly known, it is assumed that some reasonable ranges at which the given machine is operating should be known to the person performing the measurements. Once the signal is band-pass filtered it is subject to amplitude demodulation to obtain the modulating function by means of the Hilbert transform. Simultaneously a matrix of signals is created which contains a number of test signals, each of length equal to the length of the demodulated signal. Each of the signals in the matrix is of different frequency. The range of frequencies spans from the lowest possible value (determined by the resolution in the matrix) up to twice the expected value of the shaft rotational speed. Eventually the Pearson's correlation coefficient is calculated between the demodulated signal and each of the signals from the test signal matrix, creating a vector of correlation values. The point of the highest correlation is selected as the most likely representative of the shaft rotational speed.

The mathematical basis of the approach utilized in this text are given in the following section (see Fig. 1).

2.3. Amplitude modulation

Consider two signals, a carrier signal and a modulating signal, which meet the condition that the frequency of the carrier signal is significantly greater than the frequency of the modulating function. Using the modulation property of the Fourier transform one