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# Kalman Filter Applications for Industrial Fans

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## **ABSTRACT**

The advancement of computer technology and portable FFT analyzers has allowed for implementation of more efficient techniques to determine the dynamic characteristics of rotating machinery and aid in problem solving procedures. Using parametric filtering algorithms, responses of the operating system can be tracked and extracted based on the instantaneous speed of the rotating components. This data can be used to output response spectra, system frequency response functions, and information used in balancing the rotating components.

The signal processing procedures will be developed in this thesis and applied to industrial fans common in the power industry.

## **PREFACE**

I would like to begin by thanking Manta Corporation, for providing a professional and challenging engineering environment. My experience at Manta has played a crucial role in my development as an engineer and in the completion of this degree. In particular, I would like to thank Mike Carlier and Dan Morrow for their advice, support and friendship.

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## List of Symbols

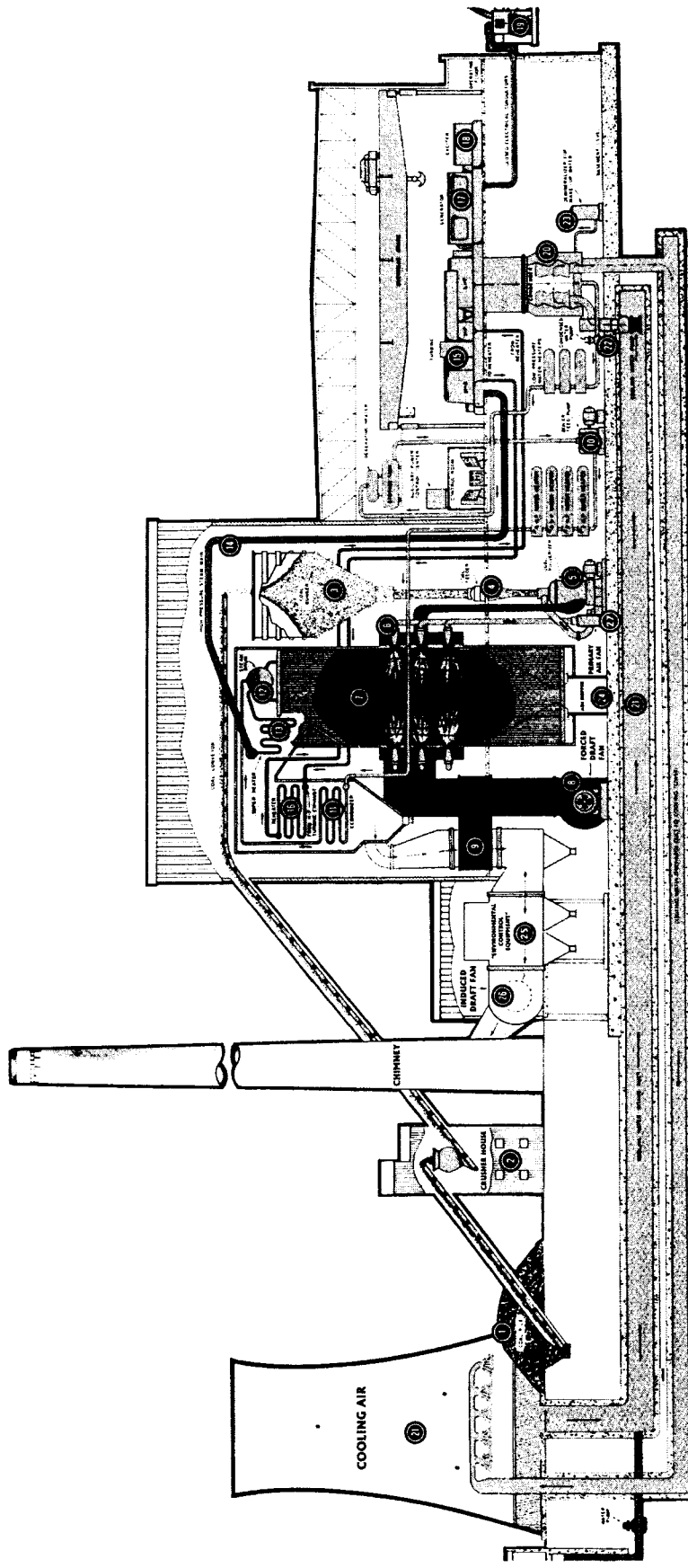
|             |                                   |
|-------------|-----------------------------------|
| RPM         | revolutions per minute            |
| $t$         | time variable                     |
| $i,k,n,j$   | counter index                     |
| $\omega$    | angular velocity (radians/sec)    |
| $a$         | amplitude of sinusoid             |
| $P,X,Y,x,y$ | amplitude in time domain          |
| $F$         | force                             |
| $\pi$       | 3.141592654                       |
| $I$         | Identity matrix                   |
| $B$         | bidiagonal Kalman filter matrix   |
| $\gamma$    | error term for Structure Equation |
| $e$         | error term for Data Equation      |
| $w$         | weighting factor                  |
| $m$         | mass                              |
| $r$         | radius                            |
| FFT         | Fast Fourier Transform            |
| $g$         | gravity                           |
| Hz          | Hertz                             |

## 1.0 INTRODUCTION

Industrial applications of signal processing techniques are often accompanied by limitations associated with the operating environment. The power industry, in general, is governed by plant outages, during which time routine maintenance is performed and any structural problems are addressed. Depending on power demands, a typical power plant can lose upwards of 200,000 dollars a day during an outage, so it is in the plants best interest to minimize down time. This limitation calls for efficient, reliable techniques to evaluate and solve problems associated with the plants performance. Figure 1.0.1 depicts a typical setup of a coal-fired electric generating plant. To maximize the efficiency of the power generating process, a system of fans and pumps are used to maintain the required air and water flow throughout the plant. Due to the extreme heat and gasses generated by the combustion process, the fans are exposed to a corrosive operating environment which can cause the fan to become unbalanced. If left unattended, the forces generated by the unbalance can begin to deteriorate the bearings as well as the supporting structure of the fan, including the foundation. Figure 1.0.2 shows an example of the type of shaft and impeller used in the fans, this particular impeller is from a Primary Air Fan (PA Fan). Figure 1.0.3 shows a typical fan housing and supporting structure and Figure 1.0.4 is a typical schematic representation of a fan assembly. Much attention is placed on the interfaces of the structure, such as the connections between the bearing and the steel pedestal, the steel pedestal and the sole plate, and the sole plate and the concrete pier. Deterioration of these areas of the structure can cause a loss in stiffness which results in lower modal frequencies of the system. When designing the supporting fan structure, modal frequencies are typically kept 20 % above or below the operating range of the fan and problems commonly arise when the natural frequencies are shifted toward the operating range. To get a feel for the operating environment and dimensional characteristics of the fans, Table 1.0.1 lists some of the typical characteristics of the industrial fans used.

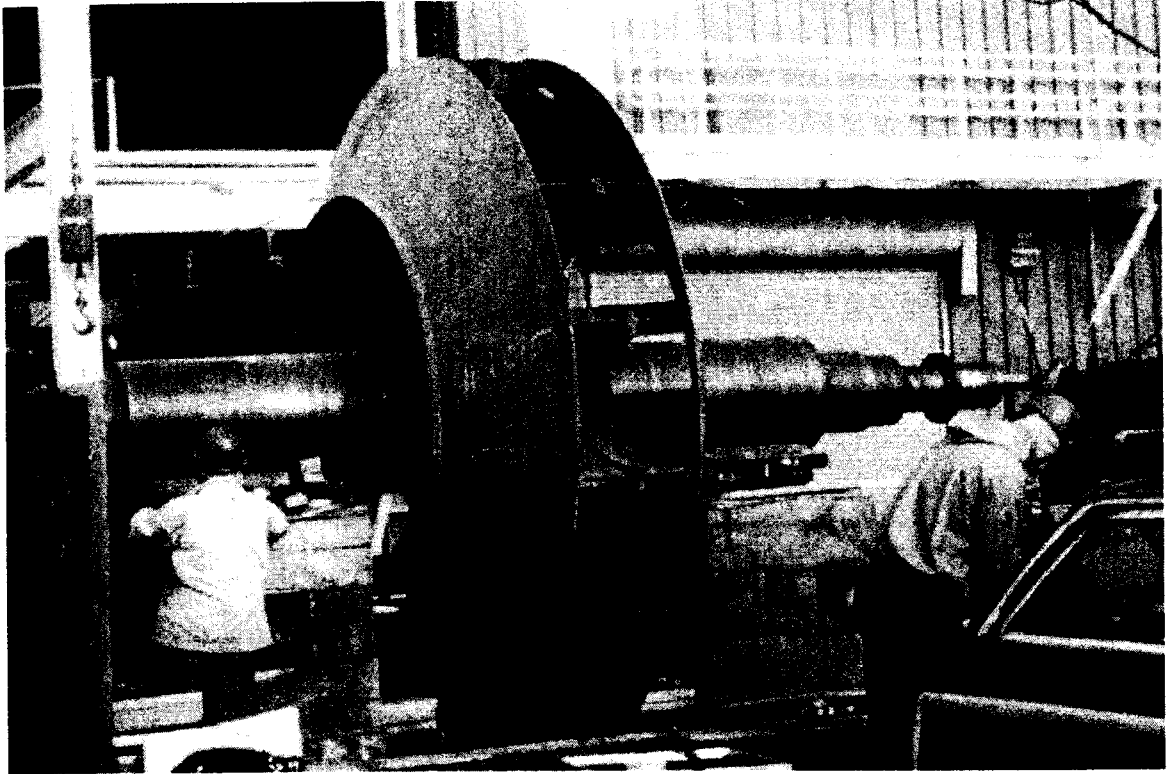
Historically, measurements made on rotating machinery during operation have been difficult due to noise that contaminates the signal. Many times this noise significantly masks the



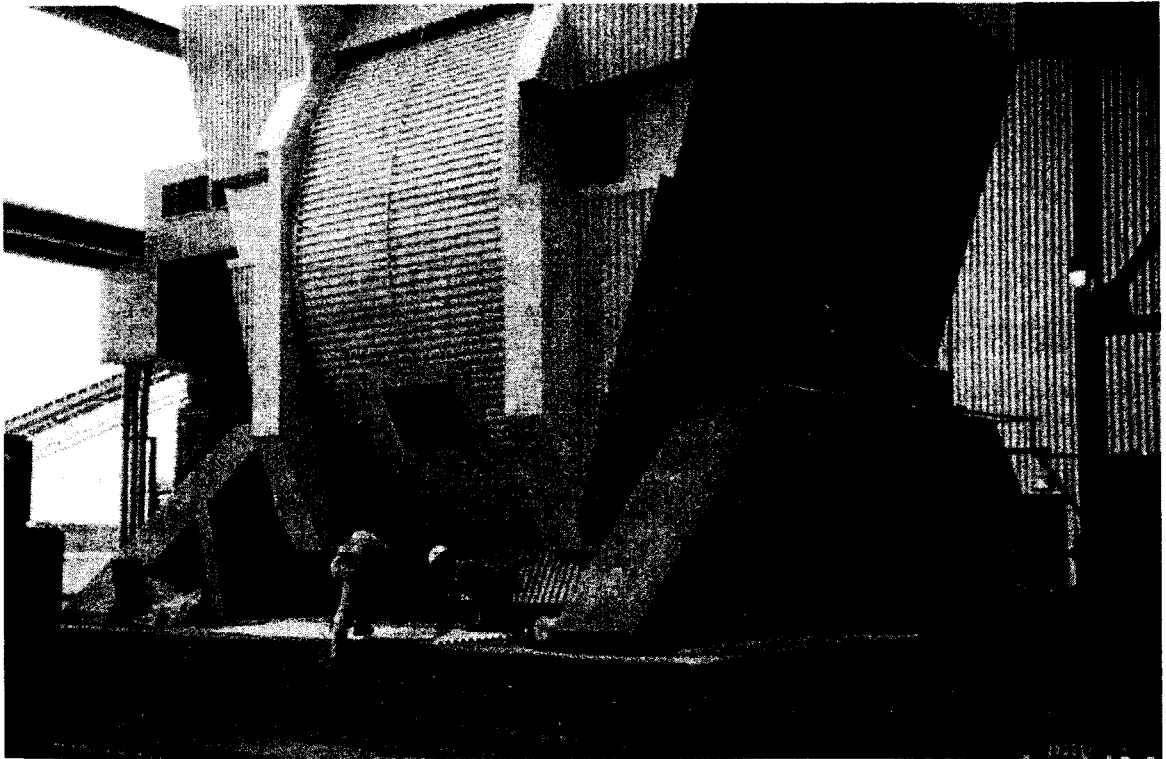


- |                   |                             |                        |                                    |
|-------------------|-----------------------------|------------------------|------------------------------------|
| 1 Coal Pile       | 8 Forced Draft Fan          | 15 Turbine             | 22 Condensed Water Pump            |
| 2 Crusher House   | 9 Air Heater                | 16 Reheater            | 23 Demineralized for Make-up Water |
| 3 Coal Bunker     | 10 Boiler Feed Pump         | 17 Generator           | 24 Ash Hopper                      |
| 4 Coal Feeder     | 11 Economizer               | 18 Exciter             | 25 Environmental Control Equipment |
| 5 Coal Pulverizer | 12 Steam Drum               | 19 Step-up Transformer | 26 Induced Draft Fan               |
| 6 Coal Burners    | 13 Superheater              | 20 Condenser           | 27 Primary Air Fan                 |
| 7 Boiler          | 14 High Pressure Steam Main | 21 Cooling Tower       |                                    |

Figure 1.0.1: Typical setup of coal-fired electric generating plant



**Figure 1.0.2: Shaft and impeller assembly used in industrial fans**



**Figure 1.0.3: Typical fan housing and supporting structure (PA fan)**

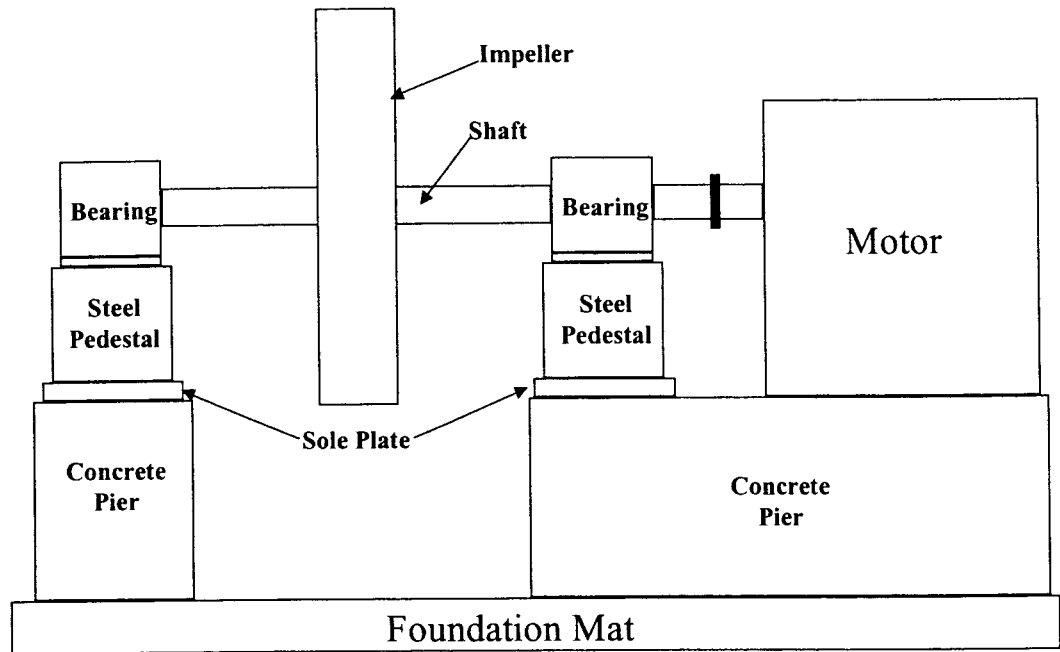


Figure 1.0.4: Schematic representation of industrial fan

Table 1.0.1: Typical characteristics of industrial fans

| Fan Type          | Diameter<br>(inches) | Speed<br>(RPM) | Function   |
|-------------------|----------------------|----------------|--|
| Primary Air Fan   | 80-100               | 720-1200       | Supplies air mixed with coal dust into the combustion chamber                |
| Forced Draft Fan  | 120-140              | 720-1200       | Air for the combustion process originates at the forced draft fan            |
| Induced Draft Fan | 120-140              | 720-1200       | Draws gasses from the fly ash collector and discharges them into the chimney |

response signal of interest and has traditionally been difficult to overcome to allow for an accurate measurement. For industrial fans it is desirable to take measurements during operation in order to discount any change in dynamic characteristics that may occur between operating and static conditions. In particular, changes in the effective boundary conditions applied by the stiffness of the hydrostatic bearings need to be taken into account.

## 1.1 Background

Signals measured on rotating systems are typically related to the speed of the rotating components, which in this case is the impeller/shaft assembly. For this type of signal the spectral components appear as harmonics of the fans' fundamental frequency of rotation. To allow for change in the fan speed, it is the signal processing objective to track the amplitude and phase of each order as a function of RPM, this process is referred to as order tracking. A number of order tracking techniques are available today that range in complexity from simple FFT based techniques to more advanced adaptive filtering algorithms that can be computationally demanding and often proprietary.

In general, order tracking algorithms rely on transformations made in either the time/frequency or the angle/order domain. The simplest is the time/frequency domain techniques where data is collected with a constant  $\Delta t$ . To work in the angle/order domain, data must be sampled at a constant  $\Delta\theta$ , where  $\theta$  represents the angle of rotation. To produce such data, time domain data may be digitally resampled to obtain angle domain measurements, or angle domain data can be recorded explicitly through the use of an encoder or ratio synthesizer used to drive a sample clock. The more traditional forms of order tracking are outlined in the following two sections.

### 1.1.1 *Fourier Transform Based Order Tracking*

The simplest method of order tracking involves performing Fourier transforms on blocks of time domain data. The results of this procedure are typically viewed as a spectral waterfall or contour plots in which a global view of the response can be examined. The accuracy of the

