The ultra precision engineering and the industrial metrology have progressed rapidly and consistently. This trend is from the direct result improving accuracies of measuring instruments and measurement techniques for supporting industrial requirements. In the spindle metrology, it is also required to reduce spindle rotation error to the nanometer or sub-microradian level. The ideal spindles must have only rotary motion with one degree of freedom; therefore, another extra motions of the spindle with five degrees of freedom (radial (2 degrees) + axial (1 degree) + angular (2 degrees)) are identified as error motions which must be eliminated or reduced. A conventional spindle measurement has contributions from the spindle motion error and the form error of the target artifact. In the conventional methods to measure radial, axial and angular motions, complicated artifacts (for example, double balls linked with a cylinder) are required. Simple artifact is favorable from the viewpoint of the accurate measurement.

In this thesis, I propose a concurrent measurement of spindle radial, axial and angular error motions using a concentric circle grating and phase modulation interferometers. In the measurement, the concentric circle grating with fine pitch is installed on top of the spindle of interest. The grating is a reference artifact in the method. Three optical sensors are fixed over the concentric circle grating, and observe the proper positions of the grating. The optical sensor consists of a frequency modulated laser diode as a light source, and two interferometers, those are Michelson and grating interferometers. One interferometer (a Michelson interferometer) in the sensor observes an interference fringe between reflected light form a fixed mirror and 0-th order diffraction light from the grating to measure the axial motion. Another interferometer (a grating interferometer) in the sensor observes an interference fringe between ±2\textsuperscript{nd} (or ±1\textsuperscript{st}) order diffraction lights from the grating to measure the radial motion. Using three optical sensors, three axial motions and three radial motions of the observed appropriate position of the grating can be measured. From the six motions, it is possible to determine radial, axial and angular motions of the spindle concurrently. Because the concentric circle grating plate is not voluminous and not heavy, this method is effective for any spindle, and does not affect the spindle original rotational motion. Since this method is based on wide-bandwidth photo sensors, it is possible to apply it to high-rotational-speed spindles. Moreover, this method is suitable for maintaining the traceability against the meter definition through the calibration of the wavelength of the light source and the grating pitch using the measurement standard. From these measured displacements, the radial, axial and angular motions of the grating, i.e., spindle, can be calculated concurrently.
In the thesis, in order to develop the measurement system of the concurrent measurement of spindle motions, two measurement techniques which consist of the quadrature detection technique and the phase modulation technique are presented. The thesis is organized by 5 chapters:

Chapter 1 - Introduction: this chapter introduces the current requirement for nanometrology and ultra precision engineering conducing to measurement of spindle rotation error to the nanometer or sub-microradian level. The motivation of the thesis is presented. The outline of the thesis is also briefly described.

Chapter 2 – Principle of the spindle motion measurement. This chapter describes the definition of five degrees of freedom spindle motion. Next, the principle of concurrent measurement of spindle radial, axial and angular motions using a concentric circle grating and three optical sensors is explained. And the last, the outline of concentric circle grating is also presented.

Chapter 3 – Principle of the optical sensor. This chapter describes the structure of the optical sensor which consists of two-axes displacement measuring interferometers (one Michelson + one grating interferometers). This measurement applied the quadrature detection (the previous research) and the phase modulation technique (the current research) in order to obtain the displacement (Lissajous diagram).

Chapter 4 – Spindle motion measurement using quadrature detection technique. This chapter shows the instrumentations and the measurement results of Michelson and grating interferometers and the compact size optical sensor performance, and the five degrees of freedom spindle motions using three optical sensors when we apply the quadrature detection technique to the interferometers. And the effects of crosstalk error to the Michelson and grating interferometers are also discussed.

Chapter 5 – Spindle motion measurement using phase modulation technique. This chapter shows the instrumentations and the measurement results of the Michelson and grating interferometers and a high rigidity compact optical sensor performance. The five degrees of freedom spindle error motions can be measured by the proposed method. The interpolation error effect to the displacement is also discussed.

Chapter 6 – Discussions, overall conclusions and future works. A review of my research work and some conclusions for the future works are discussed.