Touchdown Ball-Bearing System for Magnetic Bearings

In the event of a touchdown, ball bearings provide full support.

John H. Glenn Research Center, Cleveland, Ohio

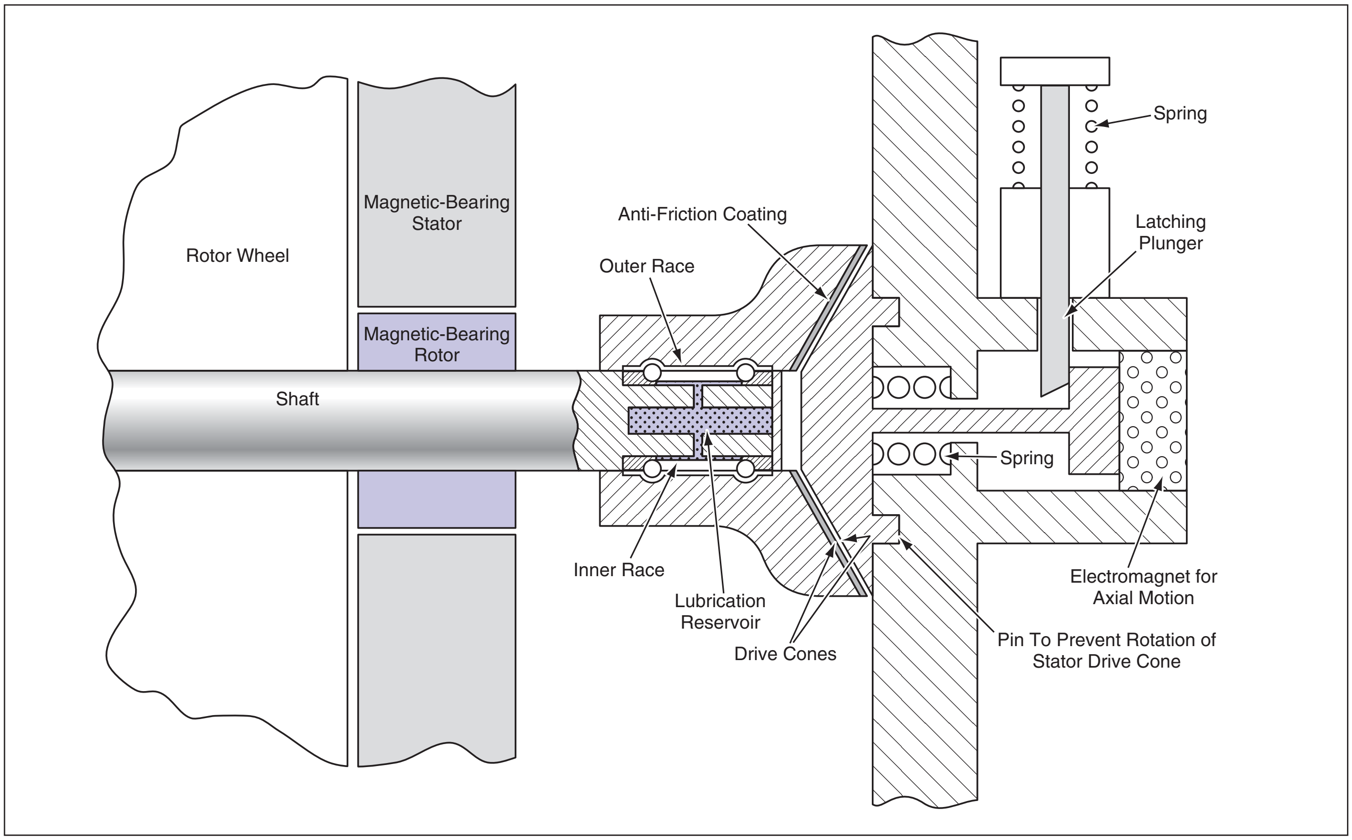
The torque-limited touchdown bearing system (TLTBS) is a backup mechanical-bearing system for a high-speed rotary machine in which the rotor shaft is supported by magnetic bearings in steady-state normal operation. The TLTBS provides ball-bearing support to augment or supplant the magnetic bearings during startup, shutdown, or failure of the magnetic bearings. The TLTBS also provides support in the presence of conditions (in particular, rotational acceleration) that make it difficult or impossible to control the magnetic bearings or in which the magnetic bearings are not strong enough (e.g., when the side load against the rotor exceeds the available lateral magnetic force).

The TLTBS includes two similar or identical subsystems, each located at one end of the rotor shaft (see figure). Mounted inside each female cone is a specially designed high-speed bearing with a built-in lubrication system. Mounted on the stator is (1) a non-rotating drive cone capable of mating with the drive cone on the rotor and (2) an electromagnetically actuated inserter mechanism that moves the stator drive cone axially between two extreme positions as described in more detail in the next paragraph. The inserter mechanism contains two electromagnets: one that withdraws the spring-loaded plunger, the second to withdraw the latch when insertion is required. Electric power is applied to the inserter mechanism only during the fraction of a second needed for the axial motion: no power is needed to keep the stator drive cone latched at either extreme position.

In one extreme axial position, denoted the inserted position, the stator drive cone is in contact with the outer-bearing-race drive cone under spring load. In this position, the ball-bearing assembly carries the full bearing load.

The other extreme axial position (the one shown in the figure) is denoted the retracted position. In this position, the stator drive cone is withdrawn from the rotor drive cone to an axial clearance of 0.010 in. (≈0.25 mm). During normal operation in the retracted position, the shaft is fully supported by the magnetic bearing. The clearance between drive cones is small enough that if the magnetic bearing fails or if an excessive side load occurs, the ball-bearing assembly can provide full support, preventing damage to the magnetic suspension and making it possible to continue (at least temporarily) operation of the machine.

Because the stator drive cone does not rotate and the rotor drive cone rotates at high speed during normal operation of the magnetic bearing, it is necessary to accommodate, and prevent frictional damage by, the slip that occurs between the two drive



The **Portion of the TLTBS at One End of a Rotor Shaft** includes a ball-bearing assembly and drive cones that can be either mated or separated by a small clearance as shown here.

cones at the time of initial contact. For this purpose, the mating surfaces of the drive cones are coated with dry lubricant films. In addition, the ball-bearing assembly contains a reservoir designed to dispense lubricant to support an elastohydrodynamic film for the specified lifetime of the system.

This work was done by Edward P. Kingsbury, Robert Price, Erik Gelotte, and Herbert B. Singer of The Bearing Consultants, LLP for **Glenn Research Center**. *Further information is contained in a TSP (see page 1).*

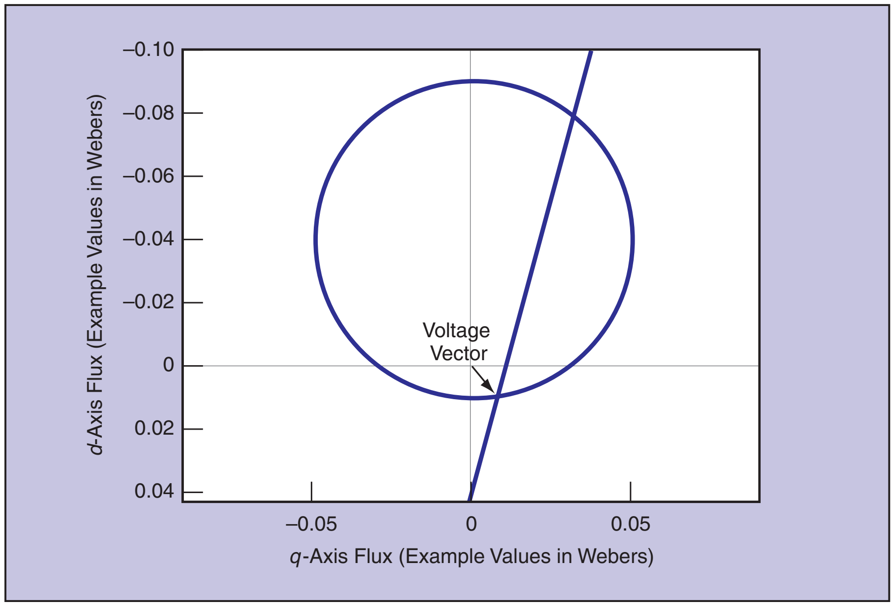
Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Commercial Technology Office, Attn: Steve Fedor, Mail Stop 4–8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-17282.

Flux-Based Deadbeat Control of Induction-Motor Torque

Graphical constructions provide insight into solutions of control problems.

John H. Glenn Research Center, Cleveland, Ohio

An improved method and prior methods of deadbeat direct torque control involve the use of pulse-width modulation (PWM) of applied voltages. The prior methods are based on the use of stator flux and stator current as state variables, leading to mathematical solutions of control equations in forms that do not lend themselves to clear visualization of solution spaces. In contrast, the use of rotor and stator fluxes as the state variables in the present improved method lends itself to graphical representations that aid in understanding possible solutions under various operating conditions. In addition, the present improved method incorporates the superposition of high-frequency carrier signals for use in a motor-self-sensing technique for estimating the rotor shaft angle at any speed (including low or even zero speed) without need for additional shaft-angle-measuring sensors.



A **Straight Line and a Circle in the *d-q* Plane** represent the desired change in torque and the desired change in stator flux, respectively. The voltage vector needed to achieve the desired change in torque and change in stator flux in one time step can be found from one of the intersections of line and the circle.

Prerequisite to a description of the method is a description of the concept of *dq* variables and *dq* coordinates. The “*d*” and “*q*” signify “direct” and “quadrature,” respectively. The *dq* coordinates lie along two orthogonal axes attached to the stator. The *dq* coordinates and the *dq* variables (which can be, for example, phase voltages and fluxes projected onto the *dq* coordinates) are commonly used in the design and analysis of induction motors.

The derivation of the method begins with the observation that a desired change in the torque of an induction motor can be represented as a straight line with units of flux on both axes of the *d-q* plane. The equation that describes the straight line can be derived from the discrete form of the induction-motor equations by use of the stator and rotor fluxes as state variables. The desired change in stator flux can be represented as a circle on the *d-q* plane. The voltage needed to achieve the desired change in torque and change in stator flux in one time step can be found from an intersection of the torque line and stator-flux circle (see figure).

Going beyond the aforementioned graphical representations, the maximum-current operating limits can be represented as a set of two lines parallel to the torque line. The maximum-voltage operating limits can be represented as a hexagon on the *d-q* plane. The maximum-voltage hexagon can be divided into four regions corresponding to an increase or decrease in torque and an increase or decrease in flux. As a result, the effect of a particular voltage vector (increase or decrease in torque or flux) can be clearly seen.

A control algorithm based on the graphical constructions and the underlying equations has been developed. The algorithm causes the synthesis of the needed excitation voltages by use of space vector modulation techniques to calculate and command inverter duty cycles. In the implementation of the algorithm without shaft-angle-measuring sensors, the high-frequency voltage needed for sensorless operation is added to the fundamental voltage and used as input for the PWM calculations. The PWM portion of the control algorithm then determines the duty cycles to generate both voltages at once. The signal from the resulting high-frequency current is processed to estimate the angular position and speed of the rotor.

This work was done by Barbara H. Kenny of **Glenn Research Center** *and Robert D. Lorenz of the University of Wisconsin. Further information is contained in a TSP (see page 1).*

Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Commercial Technology Office, Attn: Steve Fedor, Mail Stop 4–8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-17329.