

Compliant Spindles in Lapping and Testing Machines

by: B. McGlasson, Gleason Works - Rochester

American Gear Manufacturers Association



TECHNICAL PAPER

Compliant Spindles in Lapping and Testing Machines

B. McGlasson, Gleason Works - Rochester

[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

This paper presents theory, analysis, and results of a novel spindle design with application to bevel gear lapping and testing machines. This spindle design includes a rotationally compliant element that can substantially reduce the dynamic forces induced between the gear members while rolling under load. Together with a position-based servo control scheme, this technology adds stability to the gear-rolling process and in lapping machines raises maximum speeds by 50% as compared with conventional spindles.

Copyright © 2002

American Gear Manufacturers Association
1500 King Street, Suite 201
Alexandria, Virginia, 22314

October, 2002

ISBN: 1-55589-808-4

Compliant Spindles in Lapping and Testing Machines

Bill McGlasson, Gleason Works Rochester

1 INTRODUCTION

This paper presents theory, analysis, and results of a novel spindle design (patent pending) with application to bevel gear lapping and testing machines. This spindle design includes a rotationally compliant element that can substantially reduce the dynamic forces induced between the gear members while rolling under load. In lapping machines, this technology has added stability to the process and raised maximum speeds by 50% as compared with conventional spindles. In testing machines, it has reduced the influence of the machine on the quality of the test results and allowed them to retain their integrity at higher speeds. Although, particularly advantageous in direct-drive spindle designs, the compliant concept can benefit belt-driven or geared spindles as well.

The rotationally compliant element, found in at least one spindle in such machines, breaks the total spindle inertia into two parts: a relatively free forward part into which the workholding equipment and gear is mounted, and a servo-controlled rearward portion that contains the motor (or is driven by a motor), motion transducer, and chuck/dechuck mechanism. The inertia of the forward portion is minimized, whereas the inertia of the rearward portion can remain or be made large. When reduced inertia lowers the dynamic forces between the gear teeth at their point of generation, the motion transmission error (MTE) becomes truer to the gearset geometry and the excitation of the machine structure is reduced.

The presence of a highly compliant rotational element with spring-like properties also allows a novel torque control technique to be applied in a CNC machine. This technique reduces the burden on the electronic servo system to actively maintain torque in an environment of dynamic disturbances, relying instead on the laws of physics on a simple mechanism to reject these disturbances.

The theory of this highly compliant (HC) spindle concept is presented using simplified models, providing the explanation for the process benefits it brings. Analysis and simulations give additional insight into the dynamics of the system. Finally, some examples of actual lapping results are presented.

2 BASIC BEVEL LAPPING AND TESTING MACHINES

A 90-degree bevel lapping or testing machine is fundamentally simple. It is a machine tool with three independent linear axes that position two orthogonal

spindles relative to each other in space. A gear and pinion are each mounted into a spindle, and the linear axes are brought to positions such that the gear-set is held in mesh (with backlash) at its designed relative position or other nearby position of interest.

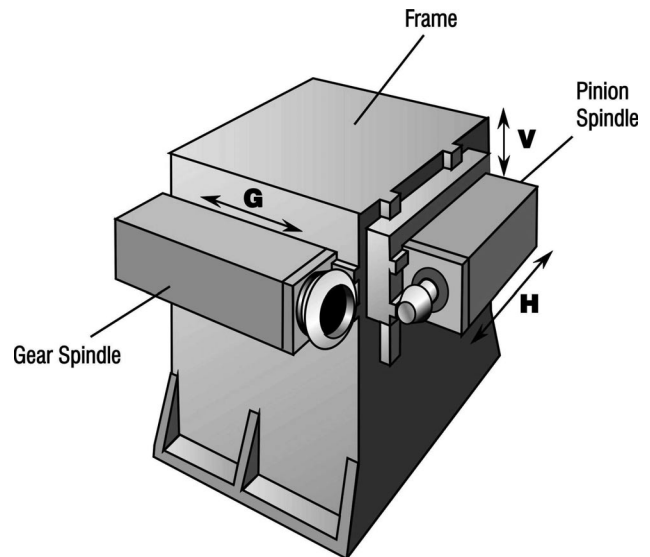


Figure 2.1 Example of lapping/testing machine configuration

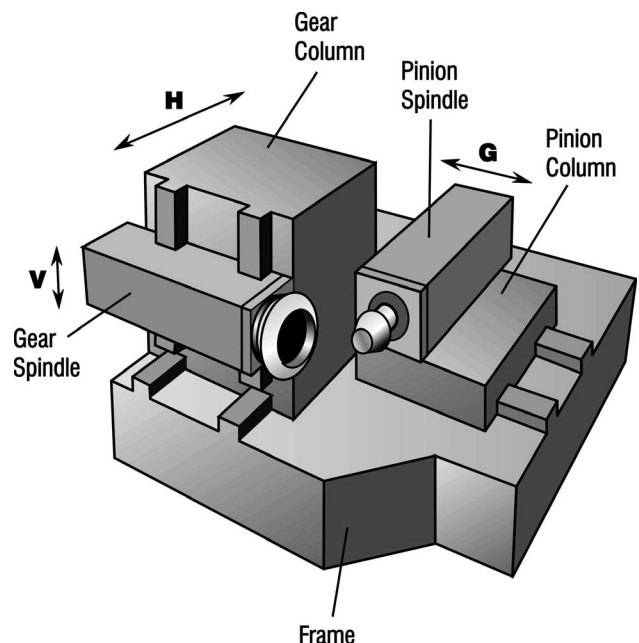


Figure 2.2 Another example of lapping/testing machine configuration

Traditionally, the pinion spindle is under velocity control and the gear spindle is under load, or torque, control.

In a testing machine, several gear quality measurements can be made. The size and position of the *contact pattern* between mating gear teeth can be discerned by rolling the set under load with a thin layer of grease-like colored marking compound pre-applied to the flanks. The rotational quality of the gear-set can be measured if high-resolution rotational sensors mounted to each spindle measure the relative rolling smoothness, or motion transmission error of the gear-set. And a measure of the gear-set's tendency to excite vibrations in the structure that holds it (*structure-borne noise*) can be made if machine-mounted accelerometers are monitored during rolling. The three linear axes can make small moves to allow investigation of gear-set behavior away from its ideal position.

A lapping machine is similar except that it has a pump and recovery system to deliver lapping compound (abrasive slurry) to the meshing zone during rolling. The lapping process refines the surfaces of the mating members to improve their running quietness and contact position. Small linear-axis motions are made during rolling to bring the lapping action across the whole tooth surface and control where metal is removed.

Achieving machine stability and good process results at high speeds has been historically more difficult on lappers than on testers. This is because lapping typically occurs at lower torques and is a metal-removal process that can "feed back" on itself in unstable ways. The greatest machine dynamic problems occur when flanks are bouncing or chattering out of single-flank contact, and this occurs most readily during lightly-loaded high-speed rolling— exactly the requirements of high-productivity lapping. (High-speed testing, on the other hand, can usually be stabilized by increasing torque above lapping limits.) And since lapping is continually modifying the gear geometry, a small dynamic problem can lap itself into a large dynamic problem, much like repeated traffic down a gravel road can create an ever-worsening "washboard" surface.

3 OLD AND NEW COMPLIANT SPINDLE CONCEPTS

Adding compliance to a lapping spindle is not a new concept. Elastomeric (i.e. "rubber") couplings and other means have been known techniques for more than 20 years, but only a minority of machines in production has employed them. The concept of adding compliance to a tester spindle is even less common. In either application, the benefits of doing so may not be immediately obvious. In fact, it is initially counter-intuitive to many practitioners, since stiffening a system and adding inertia is often key to stabilizing a dynamic process.

So what has guided machine designers and gear process experts to seek compliance over the last several decades? A desire to achieve higher process speeds. For instance, there has historically been a practical "ceiling" in lapping of about 2200 to 2400 pinion rpm for automotive gear-sets, with truck-size parts being slower still. Attempting to operate above these speeds, even with the older compliant mechanisms, has led to bad lapping results often accompanied by prominent machine vibration. Machines with this new HC spindle technology, however, routinely and successfully lap automotive and even truck gear-sets at 3000 rpm and higher.

If spindle compliance *per se*, then, is not a new concept, why has the system disclosed here been more successful than its predecessors? Four distinctives are: 1) the magnitude of the compliance, 2) the dynamic characteristics of the compliant element, 3) the novel CNC torque control scheme of which it becomes part, and 4) its application together with directly-driven spindles.

How compliant is optimal? Prior art methods (e.g. "High Speed Lapping Machine and Method", U.S. Patent 3,807,094, Ellwanger et al., 1974; "Spindle Insert", European Patent Application 82101990.B, Konersmann et al., 1982) of compliance disclosed in the literature allow at most plus or minus a degree or so of compliant motion at the gear spindle; the present method allows about plus or minus 10 degrees, and its compliance is an order of magnitude or more higher. (In physics, *compliance* is defined as the reciprocal of the more familiar term *stiffness*. The stiffness of a spring is given as force per unit displacement. The compliance of a spring, then, is displacement per unit force. In rotational systems, compliance can be given as deg/N-m.)

Prior art devices have utilized rubber or elastomeric elements that exhibit greatly non-linear torque over displacement behavior within the machine's usable torque range. Additionally, these elements have significant dynamic damping characteristics. (Whereas true spring-like elements, however non-linear, are not velocity dependent and do not absorb energy, elements with damping characteristics are and do.) The present compliant method provides a relatively linear spring characteristic within the useful range with small physical damping.

Historically, torque in a lapping or testing machine has been achieved with a mechanical brake, or more recently with CNC servo motor torque control, applied at the gear spindle. Any compliant element, if present, was merely a passive mechanism that displaced according to the transmitted torque. Although its presence modified the nature of the dynamic disturbances transmitted from the gear-set to the torque-controller, the design and application of the torque controller remained the same. In the present method, the gear spindle motor is operated