Active control of coupled vibrations in belt drives for power transmission

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Acknowledgment

The idea for the research whose results are documented in this thesis came when I was working on vibration issues of a hybrid electric vehicle powertrain during my time as vehicle development engineer in the automotive industry. Even though at an early stage in the course of the research work I changed my professional focus towards vibrations of large steam turbine rotor trains, I managed to pursue the research and to finalize this thesis.

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Bocholt, July 2016

Abstract

In this dissertation, the development and the results of a methodology for active control of belt vibrations in drivelines that contain elastic belts as power transmission elements are described. In case of torque reversal in a belt drive, passive vibration control elements may cease to perform if their functionality is limited to a unique direction or if the positioning of the devices is not appropriate for different directions of torque flow. The methodology that is presented in this contribution provides a solution for control of belt vibrations by active control of the torque that acts on a pulley in the belt drive. A new model to describe the dynamic behavior of belt drives has been developed. The nonlinear kinematics of the belt-pulley-assembly are modeled by introduction of scleronomic constraints that define the motion of the belt in the vicinity of the belt entry and exit points on the pulleys. The free belt span is modeled as a beam in finite-element-(FE)-formulation under consideration of the influence of the prestress and of the axial motion of the belt. These features are combined to yield the "hybrid belt drive model (HBDM)", which provides a state-space representation of the belt drive dynamics under consideration of the operating conditions in conjunction with the geometric arrangement of the driveline and with the dynamic properties of the individual components of the belt drive. Since no experimentally obtained empirical parameters are required to describe the coupling of the degrees of freedom, the HBDM allows to perform analyses of the dynamic behavior of a belt drive in early design stages where no test rigs or prototype parts are available. Numerical simulations of the system response to various excitation regimes are provided. A structure-variable FE-model has been formulated to determine the internal forces and torques that occur in the belt in operating condition. It is shown, that these internal forces and torques contribute significantly to the dynamic response of the system and to the coupling of pulley rotation and the lateral motion of the belt. From the nonlinear equations of motion of the HBDM, a linearized model is derived for deployment in observation tasks and in active control scenarios. Based on this model, a linear quadratic regulator (LQR) state-feedback control loop has been designed, in which the torque of an electric machine in the driveline is controlled in order to reduce the lateral vibration of the free belt spans. The control loop does not contain additional actuators, as the control of the system motion is achieved by controlling an electric machine that is part of the original driveline configuration. The functionality of the control scenario has been shown by numerical simulations.

Kurzfassung

Die vorliegende Dissertation beschreibt die Ergebnisse der Untersuchungen, die im Rahmen der Entwicklung einer Methodik für die aktive Regelung von Riemenschwingungen in Antriebssträngen mit Riemen als leistungsübertragendem Element durchgeführt wurden. Eine Umkehr der Richtung der Leistungsübertragung in einem derartigen Antriebsstrang kann dazu führen, dass die Funktionalität von passiven Elementen zur Dämpfung von Riemenschwingungen eingeschränkt wird, wenn deren Wirksamkeit konstruktionsbedingt oder aufgrund der Einbausituation richtungsabhängig ist. Die in dieser Arbeit vorgestellte Methode ist eine Lösung zur Schwingungsreduzierung, bei der durch die Regelung des auf eine Riemenscheibe wirkenden Drehmomentes die Schwingungen des Riemens aktiv beeinflusst werden. Ein neues Modell zur Beschreibung des dynamischen Verhaltens von Riementrieben wurde entwickelt, bei dem die nichtlineare Kinematik des Riemens im Bereich des Auflagepunktes durch Einführung skleronomer Bindungen abgebildet wird. Der freie Riementrum wird als Balken in Finite-Elemente-(FE)-Formulierung unter Berücksichtigung der axialen Belastung und der Transportgeschwindigkeit des Riemens modelliert. Die Kombination dieser Teilmodelle ergibt das „Hybrid Belt Drive Model (HBDM)“, das die Abbildung der Dynamik des Gesamtsystems in Zustandsraumdarstellung erlaubt. Im HBDM werden die Betriebsparameter, die Geometrie des Riementriebes und die dynamischen Eigenschaften der einzelnen Komponenten berücksichtigt. Da das neue Modell keine experimentell zu ermittelnden Koeffizienten für die Beschreibung der Kopplung einzelner Freiheitsgrade benötigt, ergibt die sich die Möglichkeit zur Analyse von Systemen in frühen Entwicklungsphasen, in denen keine Versuchsaufbauten oder Prototypen verfügbar sind. Die Ergebnisse von numerischen Simulationen der Systemantwort auf verschiedene Anregungsfunktionen werden vorgestellt. Zur Berechnung der im Betriebszustand im Riemen auftretenden Reaktionskräfte und -momente wurde ein strukturvariables Modell in FE-Formulierung entwickelt. Es wird gezeigt, dass diese inneren Kräfte und Momente einen wesentlichen Einfluss auf das dynamische Verhalten des Systems haben und die Kopplung der Drehbewegung der Riemenscheiben und der Riementrume stark beeinflussen. Aus den nichtlinearen Bewegungsgleichungen des HBDM wurde ein linearisiertes Modell zur Verwendung in Zustandsbeobachtern und in Regelungsaufgaben abgeleitet. Das linearisierte Modell dient als Grundlage für die Auslegung eines Regelkreises mit Optimalregler und Zustandsrückführung, der zur Regelung des Drehmomentes einer elektrischen Maschine im Antriebsstrang genutzt wird, um auf diesem Wege eine aktive Reduktion der Riemenschwingungen zu bewirken. Die Regelung benötigt keinen zusätzlichen Aktuator, da die elektrische Maschine bereits Bestandteil des ursprünglichen Antriebsstranges ist. Die Wirksamkeit der aktiven Schwingungsreduktion wird durch Ergebnisse numerischer Simulationen belegt.

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