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Two control strategies for semi-active load path redistribution in a load-bearing structure

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ABSTRACT

In this paper, a two mass oscillator, a translatoric moving mass connected to a rigid beam by a spring-damper system, is used to numerically and experimentally investigate the capability of load path redistribution due to controlled semi-active guidance elements with friction brakes. The mathematical friction model will be derived by the LuGre approach. The rigid beam is embedded on two supports and is initially aligned with evenly distributed loads in beam and supports by the same stiffness condition. With the semi-active auxiliary guidance elements it is possible to provide additional forces to relieve one of the beam's supports. Two control strategies are designed and tested to induce additional forces in the auxiliary guidance elements to bypass a proportion of loading away from the spring-damper system towards the now kinetic auxiliary guidance elements. The control strategies I and II depend on the different control inputs: I beam misalignment and II desired reaction force ratio in the supports. The beam's misalignment and the supports' reaction forces are calculated numerically and measured experimentally for varying stiffness parameters of the supports and are compared with and without semi-active auxiliary kinematic guidance elements. The structure's moving mass is loaded with a force according to a step-function. Thus, undesired misalignment caused by varying stiffness as well as undesired load distribution in the structure's supports can be reduced by redistributing load between the supports during operation.

1. Introduction

In many mechanical engineering applications withstanding external loads is often one of the key tasks. In most cases, the load is transmitted from one or more transmission points through a predetermined load path to the structural support interfaces. Additionally, defined kinematics are often an important part of the functional performance in the load-bearing systems with a specified motion of structural components. An example is the compression stroke of landing gear or suspension strut in airplanes or vehicles. On the one hand, a spring-damper system often determines the main kinetic properties. On the other hand, the desired compression stroke is supported by kinematic guidance elements like torque-links or other suspension links as an auxiliary structure that link two or more parts of a primer load-bearing structure for stability reasons. The load that is distributed to the structural support interfaces is predetermined and, mostly, not subject to any changes during the

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structure's lifetime. However, if system properties, e.g. damping and stiffness or strength of the supports are uncertain or vary over time, load path redirection to bypass a proportion of loading away from the weakened structural components could be an option to prevent the structure from failure or reduced comfort. Accordingly, it might be useful to change the load path and redirect the load to the stronger support interfaces known as Structural Health Control SHC, [1]. Also, a desired support reaction force ratio achieved by load redistribution during operation might be useful if the predetermined load path is not suitable anymore.

An optimal design for the load path in a structural dynamic system such as a truss with known loading conditions and without moving structural components has been investigated thoroughly in literature, e.g. in [2,3]. In general, typical optimization parameters are specific material and geometry properties such as Young's modulus, cross sectional areas of truss members and the topology of trusses, [4]. Another approach for optimal truss design is possible via damage tolerance, [5]. In this particular approach, a simple 18-bar truss structure is designed to be resistant to collapse despite suffering initial damage. These approaches improve the dynamic structural behavior by utilizing design measures and are based mainly on passive solutions without any external energy that is introduced into the structure for adaptational purposes. When additional energy is introduced into a structure, for example with counter force generating actuators that stabilize equilibrium conditions or attenuate vibrations, a structure becomes active. Active approaches found in literature mostly aim for an improvement in the vibration or damping control to enhance the dynamic behavior of truss members. For example, in [6,7], the authors used semi-active joints with piezoelectric washers and stack actuators to improve the damping of two connected beams and a cantilever truss structure. The concept of semi-active friction force by utilizing controlled varying normal force was also considered in [8]. A summary of semi-active control strategies can be found in [9]. The change of the load capacity, though, was not quantified. However, some research was conducted for enhanced load path distribution or change with active approaches in trusses. Studies to enhance the load capacity that could lead to load path redirection were made in [10] for a simple 9-bar truss with hydraulic jacks to apply internal forces and neuronal network as controller to react on unexpected high static load. In other studies, several beams of truss structures were substituted with idealized actuators in an academic way to enhance the load capacity by modifying the load path and to react to unknown loads, [11,12]. Both approaches used actuators, which were able to change their axial length and, hence, the bending stiffness of the examined truss, to create a fully stressed state of all the beams in the truss. In systems with free to move but guided structural components within a defined trajectory like landing gears or car-suspension, (semi-) active systems are used for vibration control, [13,14]. Load path adaption or redistribution is again not addressed. Local load path redistribution was conducted in [15] to reduce crack propagation with inducing active compression forces near the crack tip. By this approach, the stress intensity at the crack tip could be reduced significantly to achieve a 20% increase of durability. However, this local approach did not take into account global redistribution of load paths through a structure neither did other approaches for crack propagation reduction summarized in [16]. The load path redistribution concept investigated by earlier own studies was used to avoid locking in two-mass-oscillator representing a quarter-car-model. In case of overloading active guidance elements provide an additional load path to bear parts of the loading, [17]. Load path redistribution by shifting load from a weaker support to a stronger one was investigated numerically in [18,19]. In case of weaker supports, the misalignment can be compensated or reduced due to semi-active guidance elements. Experimental results were not presented in these studies and the misalignment was focused as control objective. Achieving a defined load split as alternative control strategy was also not addressed.

In this work, a 2D two mass oscillator that consists of a translatoric moving mass connected to a rigid beam by a spring-damper system is used to show numerically and experimentally the possibility of global load path redistribution with semi-active friction brakes in guidance elements. On the one hand, load path redistribution might be necessary when parts of the structure become misaligned, for example the rigid beam by stiffness change in the supports due to damage leading to lowering the beam in a undesirable non symmetric way, [19]. On the other hand, it might be necessary when the desired load path differ from the predetermined one. The basic idea is to redistribute loads that normally go through the spring-damper to an alternative route through the kinematic guidance elements, [17]. Load path redistribution will be possible if semi-active friction forces are applied in the joints of the kinematic guidance elements that now become kinetic. The 2D two mass oscillator is derived from a complex load-bearing system that is currently developed in the German Collaborative Research Center (SFB) 805 "Control of Uncertainties in Load-Carrying Structures in Mechanical Engineering" at the Technische Universität Darmstadt. This load-bearing system is a Modular Active Spring Damper System (German acronym MAFDS) and serves as an example for a modular structure with passive, semi-active and active modules to study uncertainty in different approaches to control stability and vibration as well as redistribute load paths, [20].

2. Truss structure example MAFDS and test rig

Fig. 1(a) shows the 3D design model of the MAFDS. The main parts are the upper and lower truss structure, a suspension strut from a mid-range car with a coil spring and a viscous damper combined to a spring-damper system, and kinematic guidance elements to realize a defined compression stroke trajectory between the upper and lower truss, [19]. The ratio of the masses of the upper and lower truss is similar to a typical quarter-car-model. The architecture of the MAFDS is modular, for example it is possible to replace the passive suspension strut by an active spring-damper system, [21], or use piezoelastic supports for truss members for stability and vibration control, [22,23].