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Evaluation of uncertainty in experimental active buckling control of a slender beam-column with disturbance forces using Weibull analysis

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ABSTRACT

Buckling of slender load-bearing beam-columns is a crucial failure scenario in light-weight structures as it may result in the collapse of the entire structure. If axial load and load capacity are unknown, stability becomes uncertain. To compensate this uncertainty, the authors successfully developed and evaluated an approach for active buckling control for a slender beam-column, clamped at the base and pinned at the upper end. Active lateral forces are applied with two piezoelectric stack actuators in opposing directions near the beam-column' clamped base to prevent buckling. A Linear Quadratic Regulator is designed and implemented on the experimental demonstrator and statistical tests are conducted to prove effectivity of the active approach. The load capacity of the beam-column could be increased by 40% and scatter of buckling occurrences for increasing axial loads is reduced. Weibull analysis is used to evaluate the increase of the load capacity and its related uncertainty compensation.

1. Introduction

Technical load-bearing structures are designed to withstand mechanical stress. Axially loaded structures, however, may fail due to instability. When exceeding the critical compressive buckling load, a column may buckle suddenly and that may lead to the collapse of the entire structure. Buckling itself as well as any means to control buckling actively are subject to uncertainty. According to a hypothesis by the German Collaborative Research Centre SFB 805 and where this work has been conducted, uncertainty occurs when process properties of a system cannot or only partially be determined [7]. Process properties may be e.g. the axial load or load capacity. One of the aims of this paper is to quantify uncertainty in buckling and buckling control according to this hypothesis.

To investigate uncertainty in buckling and in buckling control, the authors have chosen an axially critically loaded beam-column that is sensitive to buckling and therefore sensitive to small changes in the axial load e.g. when a minimal lateral deflection out of the straight axial line occurs. This minimal deflection leading to sudden buckling may occur due to lateral disturbance forces, beam-column pre-deflection or material inhomogeneity etc. [9,10].

Modifications in geometry or material of a passive beam-column may improve stability but may also increase weight and the use of resources in many cases [5]. Safety relevant structures are often designed with a safety factor of up to ten against

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buckling [8]. However, if geometry or material shall not be changed due to constraints, active stabilisation may be applied to prevent a failure. In this case, structures may be equipped with sensors and actuators linked by control and, hence, may feature augmented functionality like compensation of imperfections and increase of the axial load capacity.

In literature, several works on active buckling control are present. In most cases, moments are applied along the beam-column's axis to compensate the lateral deflection induced by a beginning buckling. Beam-columns with length l, cross section area A and moment of inertia I and different slenderness ratio $s = l\sqrt{A/I}$ were investigated [9]. In [4], a pre-deflected beam-column of fibre reinforced composite with slenderness ratio $s=300$ is stabilised by embedded shape memory alloy wires and an increase of the buckling load of 11% is achieved.

In other research, stabilisation is based on applying moments along the beam-column's length with piezoelectric patch actuators bonded to its surface [1,3,11]. In [1], a flat steel beam-column with $s=4000$ with piezoelectric patch actuators attached to its entire surface is controlled and may bear a load up to 5.6 times above the buckling load compared to the uncontrolled beam-column experimentally. Numerical studies predict an increase of the buckling load by a factor of 8.8 by controlling the first two buckling modes for a steel beam-column with slenderness ratio $s=870$ [11]. The work reviewed focusses on the increase of the buckling load but does neither deal with imperfections or disturbances nor with uncertainty within the stabilising technology [12]. In the publications mentioned above, actuators are also attached to the beam-column surface which may be inconvenient when used in environment with changing temperature, humidity, etc. Furthermore, modifications along the active beam-column's surface also lead to higher stiffness with respect to otherwise high slenderness ratio and, therefore, lead to prevention of buckling by simply adding actuator material.

In this work, the actuation against buckling is limited to an area close to the beam-column's base to leave most of the surface free from actuators. The authors present an approach to actively stabilise a beam-column with rectangular cross-section and slenderness ratio $s=725$, clamped at the base and pinned at the upper end. The active stabilisation is achieved by controlling its first buckling mode with actively controlled forces, applied with two counteracting piezoelectric stack actuators in one plane perpendicular to the longitudinal axis. They are located close to the beam-column's clamped base with opposing orientation where deflections of the beam-column are relatively small [5]. This position, though, still needs piezoelectric stack actuators that may apply relatively high deflections but only need to apply low forces [5]. However, by implementing a real active system for buckling control, additional uncertainty arises within the stabilisation technology [6]. This paper presents an approach to evaluate the measured results on an experimental test setup with respect to uncertainty.

2. Active buckling control

Fig. 1 shows the mechanical principle of the active beam-column system. The slender beam-column of length l, width b and thickness h with rectangular cross section $A = b\,h$, Young's modulus E and moment of inertia $I = I_y \ll I_z$ is loaded axially with F_x in x-direction.

The passive beam-column may buckle in z-direction when loaded with its well-known critical buckling load [9],

$$F_{x,\mathrm{cr}} \approx \frac{\pi^2 E I_y}{(0.7\,l)^2} \quad \text{with } I = I_y = \frac{b\,h^3}{12}. \tag{1}$$

However, only a perfect homogeneous beam-column remains in its critically stable equilibrium state when it is loaded by an axial compressive load equal to its critical buckling load $F_{x,\mathrm{cr}}$. Real beam-columns, though, buckle when loaded with or even below $F_{x,\mathrm{cr}}$, because lateral disturbance forces or imperfections in the material and manufacturing may cause the beam-column to deflect slightly out of the perfect straight axial line.

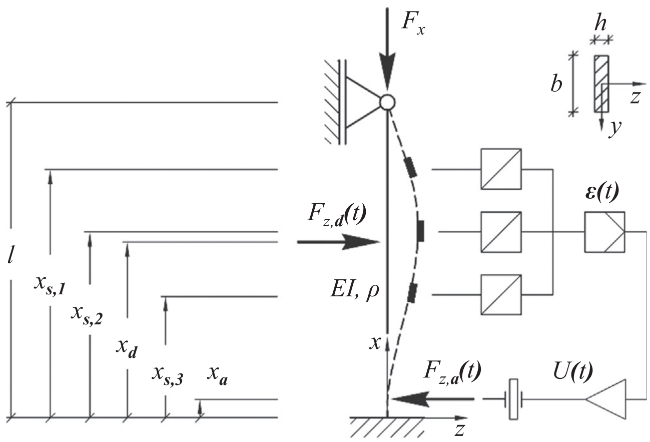

Fig. 1. Mechanical sketch of active beam-column system, cf. [6].