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Adaptive self-balancing guyed mast systems

Vadym Nesterov[1], Ivan Ćurković[2]
[1]vadym.nesterov@student.grad.hr
[2]University of Zagreb Civil engineering Faculty, ivan.curkovic@grad.unizg.hr

Abstract

Guyed masts are highly efficient structures, but their behaviour strongly depends on guy-wire pretension, load asymmetry, icing and wind actions. Existing studies mainly focus on conventional systems with independently acting guy wires, whereas adaptive self-balancing configurations remain largely unexplored. This paper proposes a pulley-based guyed mast concept combining continuous cables and passive self-tensioning mechanisms. The study identifies theoretical foundations and modelling approaches for future investigations of load redistribution, dynamic behaviour and structural response under environmental actions.

Key words: guyed masts, adaptive structures, continuous cable systems, pulley mechanisms, force redistribution, geometric nonlinearity

Adaptivni samouravnotežujući jarbolni sustavi sa zategama

Sažetak

Jarboli sa zategama predstavljaju vrlo učinkovite konstrukcije, no njihovo ponašanje u velikoj mjeri ovisi o prednapinjanju zatega, asimetriji opterećenja, zaleđivanju i djelovanju vjetra. Postojeća istraživanja uglavnom su usmjerena na konvencionalne sustave s međusobno neovisno djelujućim zategama, dok su adaptivne samouravnotežujuće konfiguracije još uvijek nedovoljno istražene. U radu se predlaže koncept jarbola sa zategama temeljen na sustavu kolotura, koji kombinira kontinuirane kablove i pasivne mehanizme samozatezanja. Istraživanje identificira teorijske osnove i pristupe modeliranju za buduća istraživanja preraspodjele sila, dinamičkog ponašanja i odziva konstrukcije pod utjecajem okolišnih djelovanja.

Ključne riječi: jarboli sa zategama, adaptivne konstrukcije, sustavi kontinuiranih kabela, mehanizmi s koloturima, preraspodjela sila, geometrijska nelinearnost

1 Introduction

Guyed masts are among the most efficient types of tall engineering structures and are widely used in telecommunication, broadcasting, meteorological, and monitoring systems. Owing to their high material efficiency, such structures enable the construction of facilities exceeding 100–600 m in height with significantly lower mass and cost compared to self-supporting towers. For this reason, guyed masts continue to represent an attractive solution for modern communication and environmental monitoring infrastructure.

Over the past decades, a considerable amount of research has been devoted to the analysis and design of guyed masts. Particular attention has been paid to the development of nonlinear analysis methods, the consideration of geometric nonlinearity of guy wires, the influence of pretension, dynamic wind effects, seismic loading, ice accretion, and structural stability. Significant contributions to the development of mast analysis methods have been made by Madugula et al. [1] on the nonlinear behaviour and dynamic response of guyed mast systems, as well as work by Hensley and Plaut [2], who investigated the influence of guy-wire parameters on structural stability and performance. A substantial body of research has also focused on the improvement of finite element models and the consideration of realistic operating conditions, including the paper [3] on the nonlinear dynamics of guyed masts under wind loading, the survey on the influence of geometric imperfections [4], and the research of Titus and Jayachandran [5] dedicated to the development of geometrically nonlinear analysis methods for guyed masts.

Despite the high level of development of current analysis methods, most existing studies consider guyed masts with fixed guy systems whose properties remain unchanged during operation. In recent years, increasing attention has been directed toward adaptive and intelligent structures capable of modifying their behaviour in response to external actions. Similar approaches are actively being developed in the fields of active vibration control of civil structures, adaptive cable-stayed systems, tensegrity structures, and robotic transformable systems. In particular, studies [6,7] demonstrate the potential for systems incorporating movable cables, pulleys, and force-redistribution mechanisms to enhance the reliability and adaptability of spatial structures.

At the same time, a review of the available literature indicates that the application of such principles to stationary guyed masts has received very limited attention. Comprehensive studies addressing the influence of pulley and block systems on force redistribution among guy wires, variations in structural stiffness, dynamic response, stability, and natural frequencies of mast structures are largely absent. Likewise, the potential of passive self-tensioning and automatic

compensation of force variations caused by wind, temperature changes, and ice accretion remains insufficiently investigated.
Therefore, an important scientific challenge is the formulation of adaptive self-balancing guyed mast systems employing pulley-based force redistribution mechanisms and passive self-tensioning of guy wires. The subsequent development of appropriate mathematical models and numerical analysis methods would enable the assessment of the influence of such systems on the stress–strain state, stability, and operational reliability of guyed mast structures, while also determining their potential for practical implementation in modern telecommunication and monitoring systems.

2 Limitations of conventional guyed mast systems

Traditional guyed masts are among the most efficient tall structures due to their low material consumption and high load-carrying capacity. However, numerous studies have shown that their operational performance is associated with several significant limitations. One of the primary issues is the high sensitivity of the structure to asymmetric wind and ice loads. Under non-uniform loading conditions, substantial force redistribution occurs among individual guy wires, leading to increased bending moments in the mast shaft, larger deformations, and local overloading of structural members [3,8]. Another characteristic feature is the pronounced geometric nonlinearity of the system resulting from the interaction between flexible guy wires and the compressed mast shaft. Variations in guy-wire tension, cable sagging, or partial loss of tension can significantly alter the global stiffness of the structure and complicate the prediction of its behaviour under loading [3].
A significant drawback of conventional guyed masts is the strong dependence of structural behaviour on the level of guy-wire pretension. Even relatively small deviations from the design values may result in changes in natural frequencies, deflections, and internal forces, thereby requiring continuous monitoring and periodic adjustment of the guy system [3]. Furthermore, studies have demonstrated a considerable sensitivity of guyed masts to initial geometric imperfections of the mast shaft. Deviations from verticality and erection inaccuracies may cause noticeable increases in stresses and reductions in structural reliability [4].
Another important issue is the vulnerability of conventional guyed masts to damage or failure of individual guy wires. The failure of a single guy wire results in a sudden redistribution of forces and may trigger progressive collapse of the entire system, as repeatedly reported in studies on the stability and failure behaviour of mast structures. Additional challenges arise under dynamic wind loading. Tall guyed masts are characterized by a large number of vibration modes who-

se properties strongly depend on guy-wire tension and operational conditions. The importance of accounting for cable nonlinearity and mast-guy interaction in dynamic analysis was demonstrated by Kaul [9]. These factors increase the likelihood of resonance phenomena and fatigue damage of structural components [3]. Ice accretion also has an adverse effect by increasing the mass of the system, reducing natural frequencies, and contributing to the development of unfavourable dynamic effects [8].

A review of existing studies indicates that the efficiency and reliability of conventional guyed masts largely depend on maintaining the appropriate level of guy-wire pretension and preserving the intended structural configuration. However, the system does not possess an inherent mechanism for the automatic redistribution of forces between different guy levels and directions. A change in loading applied to one group of cables affects the stress-strain state of the entire structure and requires consideration of the interaction among all system components. As a result, the required level of reliability is achieved through increased safety factors, strict erection requirements, and the need for periodic inspection and adjustment of guy-wire tensions during service. This limitation of conventional guyed mast systems may be regarded as the primary scientific motivation for the development of self-balancing structures employing continuous cables, pulleys, and automatic force redistribution mechanisms. The potential of such approaches is supported by studies on self-tensioning cable systems, interconnected prestressed structural components, and continuous cable systems with pulleys, which are reviewed in the following section.

3 Existing research on self-tensioning, combined guy systems and pulley-based load redistribution

The issue of maintaining stable tension in flexible elements has long been an important engineering challenge in various fields of technology. Railway overhead contact line systems represent a well-established practical example of passive self-tensioning, where counterweights and pulleys maintain nearly constant cable tension under thermal, seasonal and operational effects (Fig. 1) [10].

Additional evidence is provided by Johnston [11], who investigated a transmission tower support system with self-adjusting spring-supported guy wires (Fig. 2). The study showed that elastic elements in the guy-wire anchorage system can compensate force variations caused by external actions and structural displacements, reducing peak loads and improving force distribution.

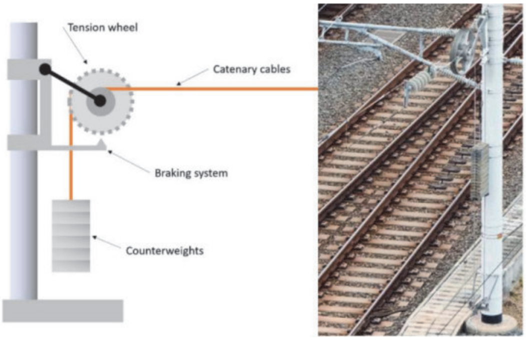

Figure 1. Constant-tension railway catenary system employing pulleys and counterweights for automatic compensation of cable elongation and contraction [10]

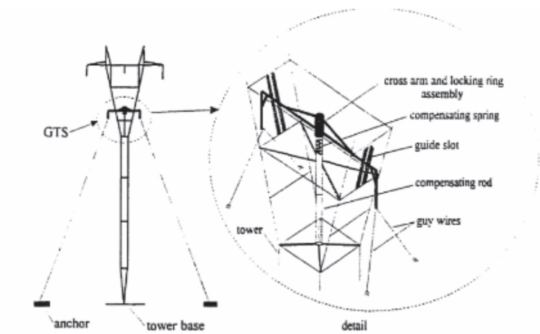

Figure 2. Guy-Wire Tension Stabilizer (GTS) with Spring-Based Self-Tensioning Mechanism [11]

Patent US4420917 [12] proposed a continuous guy-wire system for telescopic masts, in which guy wires of one level are routed through pulleys to equalize tension and simplify deployment. Although not intended for stationary masts under wind or ice loads, it confirms the feasibility of pulley-based force equalization.

Further development of the self-tensioning concept is reflected in Patent US8627614B2 from 2014 [13], which proposed a spring-based guy-wire tensioning device capable of compensating cable length variations and maintaining the required tension level, confirming the feasibility of passive self-tensioning for guyed structures.

At the same time, studies of the nonlinear behaviour of guyed masts indicate that individual guy wires do not function independently. The papers [1-3] demonstrate that a change in force within a single guy wire causes redistribution of internal forces throughout the entire system, affecting mast deflections, natural frequencies, and the stress-strain state of the structure. Consequently, the guy system should be considered as an integrated interconnected structure rather than a collection of independent cables.

An important step toward deliberate force redistribution among different guy levels was presented by Jatulis et al. [14]. The authors investigated a mast in which several guy levels were interconnected through additional links between levels. Numerical simulations demonstrated a more uniform distribution of forces among guy wires, reduced bending moments in the mast shaft, and decreased sensitivity of the structure to variations in the tension of individual cables (Fig. 3). Although no pulleys or continuous cables were employed, this study represents one of the closest known investigations confirming the effectiveness of force redistribution between different guy levels.

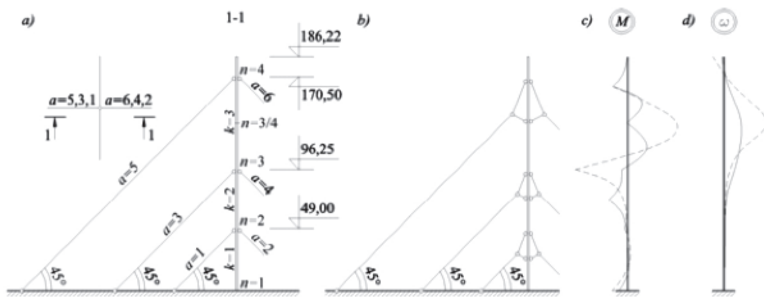

Figure 3. Comparison of a conventional guyed mast and a mast with combined guys: (a) traditional system; (b) combined guy system; (c) bending moment diagrams; (d) horizontal displacement diagrams. [14]

Further development of this concept can be observed in the work of Indriūnas et al. [15] who investigated a hybrid mast system in which a reinforced concrete shaft acts together with prestressed external stays and columns (Fig. 4). The results showed reduced top displacements, lower bending moments and increased spatial stiffness, confirming the potential of interconnected load-bearing systems for force redistribution in mast structures.

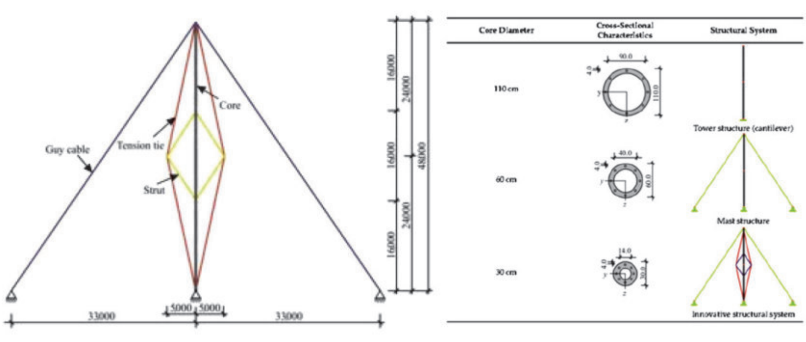

Figure 4. Innovative prestressed stayed-column mast system consisting of a reinforced concrete core, guy cables, tension ties and struts: a) Scheme; b) Comparison of conventional tower, guyed mast and innovative prestressed system. [15]

Patent CN116335676A [16] proposes a mechanically coupled cable system capable of automatically redistributing forces under external loading. Although the patent is not directly related to guyed masts, it demonstrates the feasibility of passive force equalization in systems of flexible elements.

Studies by Ma et al. [7] demonstrated that continuous cable systems with pulleys enable force redistribution and significantly influence the stiffness and mechanical behaviour of prestressed structures.

Existing studies confirm the feasibility of the individual components of the proposed concept. However, their integration within a single stationary guyed mast remains largely unexplored.

4 Mathematical framework and research methodology

Analysis of existing studies indicates that a sufficient theoretical foundation has been established for the modelling of self-balancing guyed masts employing continuous cables and pulley systems. The mathematical framework is based on several complementary research directions. The paper [7] is devoted to the derivation of equilibrium equations and the formulation of the tangent stiffness matrix for clustered tensegrity structures with continuous cables and pulleys, making it suitable as a basis for describing the stiffness characteristics of cable-pulley systems. The principles of sliding cable modelling are presented in the research [17], where it is shown that the free movement of a cable through guiding elements enables automatic force redistribution in a prestressed system.

Dynamic processes in cable-pulley systems were investigated in detail by Wang et al. [18], who developed a hybrid model of cable-pulley systems accounting for pulley kinematics and cable length variations. Further development of the theoretical framework was presented by Ma et al. [19], where nonlinear and linearized formulations of statics and dynamics for pulley-driven clustered tensegrity structures were developed and extended to finite-element analysis of systems with continuous cables and pulleys.

The practical feasibility of such an approach is further confirmed by the study [20], in which an algorithm for modelling continuous cables passing through pulley systems was developed and verified. The results obtained by the authors demonstrate the possibility of directly applying modern finite element software packages to the analysis of structures with force redistribution through pulleys.

Based on the reviewed studies, a conceptual framework for modelling a self-balancing guyed mast can be formulated. Within the proposed framework, the mast shaft can be modelled using three-dimensional beam finite elements, while the guy wires can be represented by cable elements acting only in tension, accounting for pretension and geometric nonlinearity, and the pulleys can be introduced into the numerical model through sliding constraints. An additional degree of freedom, s_i, describes the movement of the cable through the i-th pulley and enables the modelling of force redistribution between individual branches of a continuous cable. The geometrically nonlinear formulation may be implemented within the Updated Lagrangian Formulation, while the system of nonlinear equations may be solved using the Newton–Raphson method.

The proposed framework provides a basis for geometrically nonlinear static, modal, wind and icing analyses, as well as optimization studies aimed at evaluating the performance of self-balancing guyed mast systems.

Thus, future research is directed not toward the development of a new mathematical framework, but rather toward the adaptation and application of existing methods for the analysis of cable–pulley systems to stationary guyed masts. This makes it possible to formulate the main scientific objective as the quantitative assessment of the influence of continuous cables and pulley systems on the stress–strain state, dynamic characteristics, and operational reliability of guyed mast structures.

5 Conclusion

The conducted analysis indicates that individual components of the self-balancing guyed mast concept already possess theoretical, experimental, and practical justification. However, their integration into a unified system of automatic force redistribution for stationary guyed mast structures remains largely unexplored. The development and investigation of such structures represent a promising research direction that has the potential to expand the design capabilities of next-generation adaptive guyed mast systems. The proposed concept provides a basis for future numerical and experimental investigations aimed at evaluating the influence of continuous cables and pulley systems on the behaviour of guyed mast structures under operational and environmental loading conditions.

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