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Detection of Tensile Forces in Cable-Stayed Structures Using the Advanced Hybrid Micro-Genetic Algorithm

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***Abstract*—**This study deals with an advanced numerical techniques to detect tensile forces in cable-stayed structures. The proposed method allows us not only to avoid the trap of minimum at initial searching stage but also to find their final solutions in better numerical efficiency. The validity of the technique is numerically verified using a set of dynamic data obtained from a simulation of the cable model modeled using the finite element method. The results indicate that the proposed method is computationally efficient in characterizing the tensile force variation for cable-stayed structures.

***Keywords*—**Tensile force detection, cable-stayed structures, hybrid system identification (h-SI), dynamic response.

I. Introduction

Of the many condition assessment techniques for cable-stayed structures available today, system identification methods are based on detecting the changes in static or dynamic behavior of a cable [1]-[3]. The tensile force of cables could be inversely determined by using mathematical models based on the taut string theory or axially loaded beam theory from natural frequency data. These works, based on simplified analytical approaches, have limited capabilities in dealing with complex problems, primarily due to their limitations in handling real cable shapes in the analysis. The differences between the real structural system and mathematical model for various cables make deleterious contributions to the accurate detection of the tensile force [4]. In addition, Reference [5] presented the significance of the flexural rigidity of cables in determining tensile forces. It reported that the tensile force induced from the simplified string model, which does not consider flexural rigidity, is not reliable for most cases. The difference becomes more dramatic for cases of the geometrical shape of cables, construction tolerances, or support conditions. Reference [6] proposed a method for detecting tensile forces by combining static and dynamic identification techniques, which reflect the characteristics of the tie-rod structural system. Reference [7] carried out the identification of the tensile force in high-tension bars using modal sensitivities. Reference [8] developed a system identification technique to determine the tensile force and various rigidities of cables simultaneously by using the finite element method and sensitivity equation. They proved the proposed method through lab-scale and field test.

These works, based on the local optimization algorithm (LOA), have limited capabilities in dealing with complex problems, primarily due to their limitations in handling assumed initial conditions in the analysis. They have several limitations, such as divergence and instability problems, during numerical calculations. Especially, the trap problem of false minimum is frequently observed for large and complicated structures. In recent years, global optimization algorithms (GOA), such as neural networks, genetic algorithms (GAs), and simulated annealing methods have been developed and promisingly applied to the field of structural identification. Among them, GAs attracted our attention because not a great deal of data was needed in advance. This is an advantage over natural frequency-based neural network methods that require prior knowledge of both the modal frequencies and the modal shapes to train the neural network and to detect the structural damage. Reference [9] presented a microgenetic algorithm that is able to identify the location and extent of damage in plate-type structures using only the frequency information. Reference [10] suggested a differential evolutionary algorithm to determine external tendon forces and Rayleigh damping coefficients.

Despite the broad spectrum of applications, the conventional GAs usually require a large number of iterations, and thus high computational cost. To solve an inverse problem using a GA, it is necessary to carry out iterative forward computations for each individual. Reference [11] developed a hybrid genetic algorithm (h-GA) to reduce the iterations by using the organic-hybridization technique. For a cable-stayed structure, global optimization algorithms such as GAs and an efficient sensitivity method could serve a dominant role in improving the convergence. Thus, the study is further extended in this investigation to take into account the combined effects of the hybrid microgentic algorithms (h-GA) and the sensitivity equation. The focus is on the detection of tensile forces using the hybrid algorithms and comparison with different approaches. Finally, the numerical results are verified by comparing them with measurement data obtained from a laboratory-scale test of cables.

II. Hybrid Micro-Genetic Algorithm

The hybrid micro-genetic algorithm developed in this study is based on the finite element model considering the geometrical shape, end conditions, and construction tolerance of cables. To improve the final convergence, it also uses the sensitivity equations among the existing LOA. Fig. 1 illustrates the hybrid procedure used in this study. The hybrid system identification algorithm consists of h-GA in GOA and the sensitivity-updating algorithm in LOA. It also uses the post-hybridization procedure to avoid the local convergence,

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which the GOA provides the initial value to LOA.

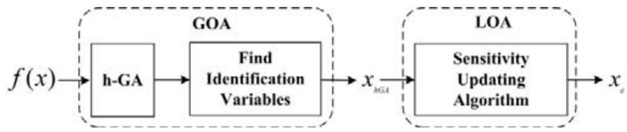


Fig. 1 A schematic representation of the proposed method

In order to decide a proper diverging point between GOA and LOA, the number of generations (n_G) in h-GA and iterations in SUA should be assigned in advance. In this study, the relationship between n_G and identification factors is assumed to be a linear combination as (1). Reference [12] proposed the number of generations in GA using the Fibonacci series.

$$\mathrm{n_G = N_a p} \tag{1}$$

$$\mathrm{n_L = Ceil(n_{GOA}/2P)} \tag{2}$$

where, $\mathrm{N_a}$ and p(=3) denote an arbitrary number and the number of identification factors, respectively.

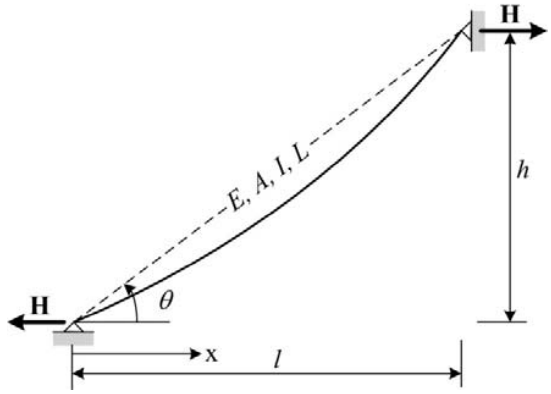


Fig. 2 A sagged cable model for numerical examples

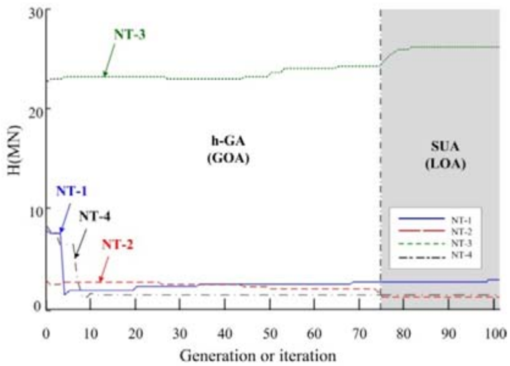
III. Numerical Examples

Fig. 2 shows a sagged cable model for numerical tests, and the mechanical and material properties of four-types (NT1~NT4) cables used in this study are tabulated in Table I. In the table, λ^2 and ξ represents characteristics of cables and can be expressed as

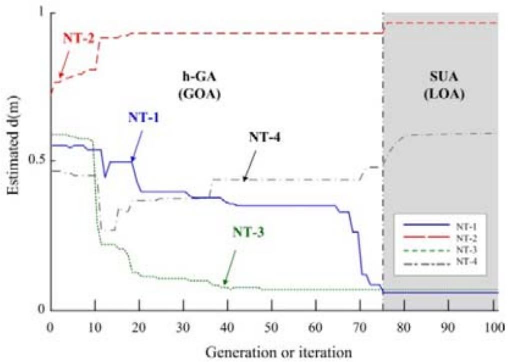
$$\lambda^2 = \frac{\mathrm{EA}}{\mathrm{H}}\frac{\mathrm{l}}{\mathrm{L_e}}\left(\frac{\mathrm{mg\,L_e}}{\mathrm{H}}\right)^2, \tag{3}$$

$$\mathrm{L_e} = \int_0^l \left(\frac{ds}{dx}\right)^3 dx \cong \mathrm{L}\left[1+\frac{1}{8}\left(\frac{\mathrm{mg\,L}}{\mathrm{H}}\right)^2\right],\ \xi = \mathrm{L_e}\sqrt{\frac{\mathrm{H}}{\mathrm{EI}}} \tag{4}$$

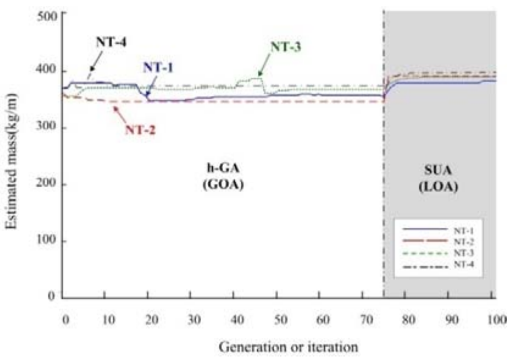
Fig. 3 shows the convergence process to find the parameters H, d, and m. It can be observed that H and m converges after approximately 10~20 iterations while d is found after approximately 70~80 iterations. It is also noted that there exists a plateau in detecting the horizontal force as shown in Fig. 3 (a). This means that the procedure could converge into a wrong value before it reaches the correct value. Fig. 4 shows the convergence of the object function for the best member of the population in each generation. We can observe from the figure that the GOA converges within 60 generations in each case. We may conclude from these results that the proposed h-GA in GOA satisfactorily provides the initial information for SUA in LOA.



(a) Horizontal force (H)



(b) Effective diameter (d)



(c) Mass per unit length (m)

Fig. 3 The convergence processes to find: (a) horizontal force, (b) effective diameter, and (c) mass per unit length for NT-1~4.

TABLE I
MATERIAL AND GEOMETRIC PROPERTIES FOR FOUR NUMERICAL INCLINED CABLE MODELS

Properties	NT-1	NT-2	NT-3	NT-4
λ^2	0.079	5075.8	1.41	0.508
ξ	1923.5	3.0295	50.459	505.113
$\theta(°)$	30	30	30	30
$L(m)$	100	100	100	100
$m(kg/m)$	400	400	400	400
$H(MN)$	2.9036	0.7259	26.1325	0.7259
$E(GPa)$	1.5988	17.186	20826.0	0.00478
$A(10^{-3}m^2)$	7.8507	7.6110	7.8633	273.45
$d(m)$	0.1	0.984	0.1001	0.5901
$I(10^{-6}m^4)$	4.9535	4.6097	4.9204	5950.6
$T_{\max}(MN)$	3.4409	0.9348	30.261	0.9348
$T_{\text{mean}}(MN)$	3.3539	0.8427	30.175	0.8427
$T_{\min}(MN)$	3.2711	0.7675	30.091	0.7675

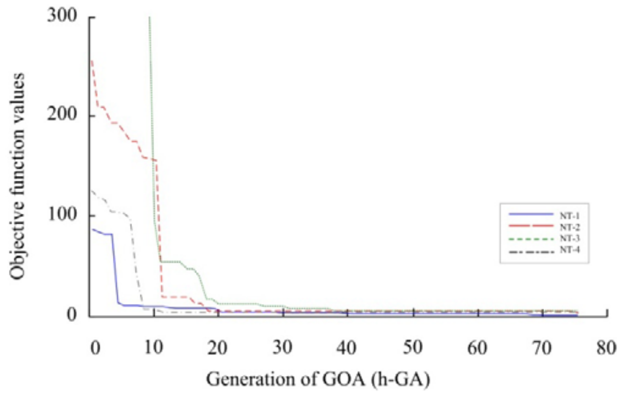


Fig. 4 The change of objective function value for NT-1~4

The proposed method using the h-SI is compared with those of various existing approaches as listed in Table II. In the case of applying SUA, it shows excellent detectability as errors were within 1.2%, except for NT-1, because it uses the FE model which reflects the geometrical characteristics of cables such as the sag. For the same iteration (113 times), the detectability for the case of NT-1 is the lower than others because of their complexity due to small sagged geometry and large flexural stiffness. For the increased iterations, it can provide fast convergence to the near optimal solution.

IV. CONCLUSION

In this paper, a hybrid micro-genetic algorithm is developed to detect tension forces of cable-stayed structures subjected to impact loads. For the numerical analysis, we developed a finite element computer program using a combination of LOA and GOA, which can avoid premature convergence due to incorrect initial values. To verify the numerical analysis, we have carried out dynamic experiments for lab-scale cable structures, and the results obtained were in good agreement with those computed using numerical methods. The detection characteristics for the tension of a cable stayed structure subjected to impact loads are analyzed by considering various mathematical theories, especially for sag effects of cables. The current analytical approaches for the tension detection of cable structures are insufficient in accurately determining the complicated dynamic and geometrical effects for cable-stayed structures. It may be concluded from this study that the proposed h-SI method using LOA and GOA should be used to identify the tension of cable structures with complicated dynamic behaviors for better accuracy. However, the requirement for executing many forward procedures increases the need for further developing the algorithms for faster convergence and better computational efficiency. It will be also necessary to prove the concept from further experimental studies for real cable-stayed long-span bridges.

TABLE II
ESTIMATION RESULTS OF IDENTIFICATION VARIABLES WITH VARIOUS METHODS FOR NUMERICAL CASES

Case	$\mathbf{x}^p$	True value	Methods		
			LOA	GOA	h-SI
NT-1	$H(MN)$	2.904	2.690	2.912	2.749
	$d(m)$	0.100	0.096	0.031	0.097
	$m(kg/m)$	400	370.587	112.617	378.735
	$T_{\text{mean}}(MN)$	3.354	3.106	3.362	3.174
	$EI(Nm^2)$	7.848e+03	6.749e+03	7.248e+01	6.948e+03
	$EA(MN)$	12.557	11.645	1.207	11.815
NT-2	$H(MN)$	0.726	0.726	1.211	0.726
	$d(m)$	0.984	0.984	0.980	0.984
	$m(kg/m)$	400	399.800	230.698	399.800
	$T_{\text{mean}}(MN)$	0.843	0.838	1.398	0.838
	$EI(Nm^2)$	7.909e+08	7.906e+08	7.781e+08	7.906e+08
	$EA(MN)$	13,069	13,067	12,963	13,067
NT-3	$H(MN)$	26.133	26.058	24.020	26.058
	$d(m)$	0.1001	0.100	0.103	0.100
	$m(kg/m)$	400	398.856	116.918	398.856
	$T_{\text{mean}}(MN)$	30.175	30.089	27.736	30.089
	$EI(Nm^2)$	1.026e+08	1.022e+08	1.151e+08	1.022e+08
	$EA(MN)$	163,894	163,567	173,528	163,567
NT-4	$H(MN)$	0.726	0.734	0.626	0.730
	$d(m)$	0.5901	0.592	0.337	0.592
	$m(kg/m)$	400	402.530	399.218	402.530
	$T_{\text{mean}}(MN)$	0.843	0.848	0.723	0.843
	$EI(Nm^2)$	2.845e+04	2.882e+04	3.026e+03	2.880e+04
	$EA(MN)$	1.307	1.316	0.426	1.315

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