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Evolution based statistical optimization technique to design the smart structural system for large aerospace structures

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1. INTRODUCTION

A numerical approach for genetics based statistical optimization technique is used to design the smart structural system for aerospace structures. An evolutionary based optimization technique like genetic algorithm (GA) has come into prominence. The reason for developing evolution based algorithm for optimization is for its robustness and randomness. Other numerical tools that are used for optimization are generally gradient based algorithm, where there is possibility of occurrence for a local optimum value. The GA developed is a niche-micro GA, where termination criteria are set in order to restart the algorithm. Stage-wise multiple objective functions and multiple termination criteria are incorporated to improve the computational effort. The current approach is very much robust to design a smart structural system through optimization for its maximum structural performance. In order to achieve maximum structural performance for the smart structural system, it is necessary to appropriately position the active elements. Here the genetic algorithm is amalgamated with finite element to perform a statistical based optimization to locate the position and size of active structural elements i.e. actuators/sensors. Majorly, nowadays the actuators and sensors that are preferred for smart structures design (i.e. Piezo patches, Piezo composite, SMA wire, SMA composite etc) develop induced strain under an external applied field. It becomes necessary to optimize the smart structures using the following parameters such as static strains, modal dynamic strains, size of the actuators/sensors, induced strain etc. A scaled T-Tail model is taken as an illustration to carry out the GA analysis for the location and sizing of PZT actuator/sensor. The structural parameters such as static strains, modal dynamic strains and geometry details are taken from NASTRAN and then interfaced with MATLAB to perform the statistical optimization analysis.

The generation of strain database is the input for actuators/sensors locations. The following steps have been adopted for this optimization procedure.

Step 1: Creation of elemental strain database using static and dynamic analysis

Step 2: Two levels of optimization are performed

  a. Optimization of number of actuators and their location using static strain data
  b. Optimal distribution of actuators to target critical modes using dynamic strain data

In step 1, a von-Mises strain database is created with an assumption that actuators/sensors are located at different components i.e. selecting the highly strained elements from the major components. The major components of scaled T-Tail are made as substructure from vertical tail (VT) and horizontal tail (HT) and as follows VT Front Spar, VT Middle Spar, VT Rear Spar, VT Ribs Bottom, VT Ribs middle, VT Ribs top, VT Skin Left, VT Skin Right, HT Front Spar, HT Rear Spar, HT Ribs Bottom, HT Ribs middle, HT Ribs top, HT Skin Top, HT Skin Bottom.

In step2, the results of static analysis are used in the initial population generation for genetic algorithm (GA), which becomes primary step for GA analysis. In this primary step, it is necessary to develop a logic based initial population for GA. In this procedure, the initial population is generated to select the minimum number of finite elements required to form actuator set (i.e. group of patches) for GA analysis. Initial population considers the size of actuator and static strains for GA. The nature of strain depends on the type of deformation to be considered i.e. whether the dynamic simulation represents bending or torsional or coupled deformation; for bending deformation, we consider von-Mises strains and for torsion, the shear strains and combination of these strains to represent coupled deformations.

The present issue is analyzed using von-Mises static and modal dynamic strain. The strain data must be normalized for each load case separately; it has to be done with respect to maximum strain of all the entire substructure components. In order to estimate the required number of actuators, it is necessary to decide upon the control performance either in terms of induced force or strain. The approach used here is induced strain effect.

2. LITERATURE SURVEY

Genetic algorithm based optimization scheme was developed by Raja and Balasubramaniam (2003) to optimize actuator location for vibration control application through finite element for a smart plane frame structure. Dynamic strain data was used to reduce the population size, so that search domain become simpler. With optimally placed extension type piezoelectric actuators, the first four elastic modes of a framed structure was shown using a velocity feedback. An efficient micro GA was developed by Sheng and Kapania (2006) for the placement of large number of piezoelectric patches for shape control application. This approach was compared to other heuristic based technique and proved it to be more efficient in terms of computational effort and accuracy as well. Kapania and Sheng (2006) developed an improved GA to find optimal locations and optimal voltages under thermal loading conditions. The efficiency of the algorithm was proven by the number of possible solutions that could be solved. Frecker (2003) addressed issues based on optimization techniques to design smart structure using topology optimization, actuator and sensor location for different smart materials namely piezoceramic, shape memory and magnetostrictive. The basic concept in the development of GA has been discussed by Goldberg (1989). GA analysis for actuator and sensor location on plates and shell was carried out using in-house finite element code by Kumar Gajavalli (2003). Rajasekaran and Ramasamy (2002) showed the application of GA for the optimal design of composite laminate for different lay-ups, fiber and matrix configurations. Further the improvement of in-house genetic algorithm code was addressed by Rahul Koul (2003).

3. PROBLEM FORMULATION

The strain data generated is the result of elastic response as shown in figure 1a for different loadings, since this produces a reaction; we assume P_{mech} as disturbance and structural element as actuator which is actuated by an electric field. Let us consider the disturbance strain is going to be taken by the actuator. Since PZT actuators are strain based, the induced strain is directly a function of elastic stiffness of the structure on which it is going to deform. Highly strained elements reflect higher stiffness (lower deformation) zones in the elastic structure.

Open loop equilibrium condition (static)

$\varepsilon_{elastic} = \varepsilon_{dist}$ (disturbance potential, for convenient expressed as strain)

Closed loop equilibrium condition (static)

$\tilde{\varepsilon}_{elastic} = \varepsilon_{dist} - \varepsilon_{actuator}$ (elastic strain is reduced because the actuator strain works against the disturbance potential)

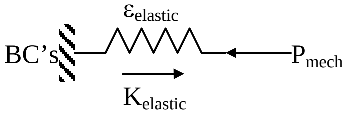


Figure 1a: Elastic system behavior

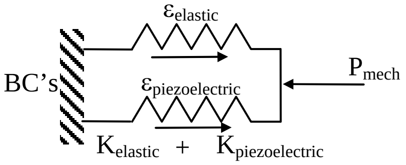


Figure 1b: Piezoelastic system behavior

With this logic, actuator strain values (induced) could be estimated directly from the elastic strain data (normalized) to form the initial pool for specified control (figure 1b). It is important to decide first on the percentage of control. This is done before starting of the genetic algorithm program.

$\varepsilon_{open} = CPI * \sum_{1}^{nel} \hat{\varepsilon}_{EID}^{elastic}$; ε_{open} = Open loop strain, $\hat{\varepsilon}_{EID}^{elastic}$ =Elemental elastic strain,

CPI= control performance index (varies from 0 to 1), which is based on the amount of control required.

The design pattern of the genetic algorithm module is shown in figure 2 as a flowchart. The flow chart explains the complete procedure for the optimization solution through GA. Here the structure of GA for this numerical study is as follows.

1. *Initial population with logic based design:* For the generation of initial population, two approaches are followed; first approach considers the area of sub-structures and the number of actuators required is taken for the second approach. The procedure is initiated by selecting the highly strained elements i.e. based on elastic strain (normalized), where the induced strain (piezoelectric effect) and open loop strain (disturbance) are reordered according to the normalized elastic strains. In the first approach, a percentage area of the substructure is assumed to form the active substructure based on the highly strained elements. In the second approach, the area of a patch (actuator/sensor) is multiplied with total number of patches required for a particular substructure to form the active substructure. The area of the active substructures is computed by these two approaches, and then it is compared, whichever predicts maximum area will form initial population for that loading condition. This procedure is carried out for each substructure.
2. *Local fitness function or local objective function (Maximization function):* Here the criteria for this objective function are to get maximum efficiency of an actuator due induced strain effect, where API (Actuator performance index) plays

an important role for the actuator performance. API indicates amount of voltage that can be applied on the actuator, which is represented in non-dimensional form (i.e. 0 to 1). This API could be constant or variable type. In this function, initially a set or group of actuators is selected for particular a generation and, then for the next generation again a new set of actuators is again selected. This process is continued until specified of number of generation is attained or fitness value for an actuator is around 95%. Through this process, a single actuator will be selected from a group of actuators after specified number of generation. The fitness function is follows:

Maximize F: $\mathrm{API}*\hat{\varepsilon}_{\mathrm{EID}}^{\mathrm{induced}}$ *(Variable API) or* $\mathrm{API}*\hat{\varepsilon}_{\mathrm{EID}}^{\mathrm{induced}}$ *(Constant API).* $\hat{\varepsilon}_{\mathrm{EID}}^{\mathrm{induced}}$ = Closed loop strain; API= (range is from 0 to 1).

3. *Niche:* Always holds the global optimum value for a specified of generation
4. *Actuator set formation/ constraint:* This check for the required number of actuators is reached or not.
5. *Global fitness function or global objective function (Minimization function):* In this function, the selected actuator will be evaluated for its induced strain performance on the global strain; this iteration will be continue till the specified no of actuators are reached or the value of objective function reaches minimum value i.e. reducing global strain effect (100 % i.e. the index value =1) through induced strain (10% i.e. the index value is ≤ 0.1, *for eg: 1-0.9=0.1*) of the required value.

Minimize F: $\dfrac{\varepsilon_{\mathrm{open}}-\sum\limits_{\mathrm{nact}=1}^{\mathrm{mact}}\mathrm{API}*\hat{\varepsilon}_{\mathrm{EID}}^{\mathrm{induced}}}{\varepsilon_{\mathrm{open}}}$ *(Variable API) or* $\dfrac{\varepsilon_{\mathrm{open}}-\mathrm{API}*\sum\limits_{\mathrm{nact}=1}^{\mathrm{mact}}\hat{\varepsilon}_{\mathrm{EID}}^{\mathrm{induced}}}{\varepsilon_{\mathrm{open}}}$ *(Constant API) or Minimize F:* $1-\dfrac{\sum\limits_{\mathrm{nact}=1}^{\mathrm{mact}}\mathrm{APF}*\hat{\varepsilon}_{\mathrm{EID}}^{\mathrm{induced}}}{\varepsilon_{\mathrm{open}}}$ *(Variable API) or* $1-\dfrac{\mathrm{APF}*\sum\limits_{\mathrm{nact}=1}^{\mathrm{mact}}\hat{\varepsilon}_{\mathrm{EID}}^{\mathrm{induced}}}{\varepsilon_{\mathrm{open}}}$ *(Constant API)*

The optimization procedure opts for multiple objective functions, where it has a global optimum function and also local optimum. The constraints are set for actuator voltage, control performance index and actuator performance index. These constraint parameters vary based on the performance required for the control of each vibration mode. Global optimum looks at the maximum number of actuators required and performance of the actuator set. Local objective function chooses best actuator for that generation.

The T-Tail model is taken for GA analysis is shown in figure 3a; then looking at the feasibility of placing a patch actuator/sensor the model is reduced as depicted in figure 3b for initial population. This model is further taken into the initial population calculation and fed into the GA module for patch location identification of actuators/sensors for individual modal participation and also for combined modal participation.

4. RESULTS & CONCLUSIONS

The micro-GA procedure is successfully implemented and studies based on scaled T-tail model have been carried out for the considered elastic modes, namely HT-Antisymmetric, HT-Symmetric and VT-Lateral. The analysis has been done for individual elastic mode and then a combined effect of the elastic modes is also shown. The sizing of patch actuator is approximately done. The figure 4 shows combined GA analyses for HT Symmetric and HT Antisymmetric modes for actuator location (approx. 20 patches). The location for 20 actuators with induced strain effect, where the effect of HT Antisymmetric and HT Symmetric modes are combined and presented in table 1, and also figure 5 illustrates the planform location of the selected actuators for the above mentioned case study. Further, the independent case study has been carried out in order to analyze the actuator of VT Lateral mode. This concludes the numerical studies to be presented for the paper. Finally, table 1 show that the present technique adopted for actuator location is well suited for large structures, where the implementation of the algorithm is simple, robust and efficient and also explains the actuator efficiency by induced strain effect.

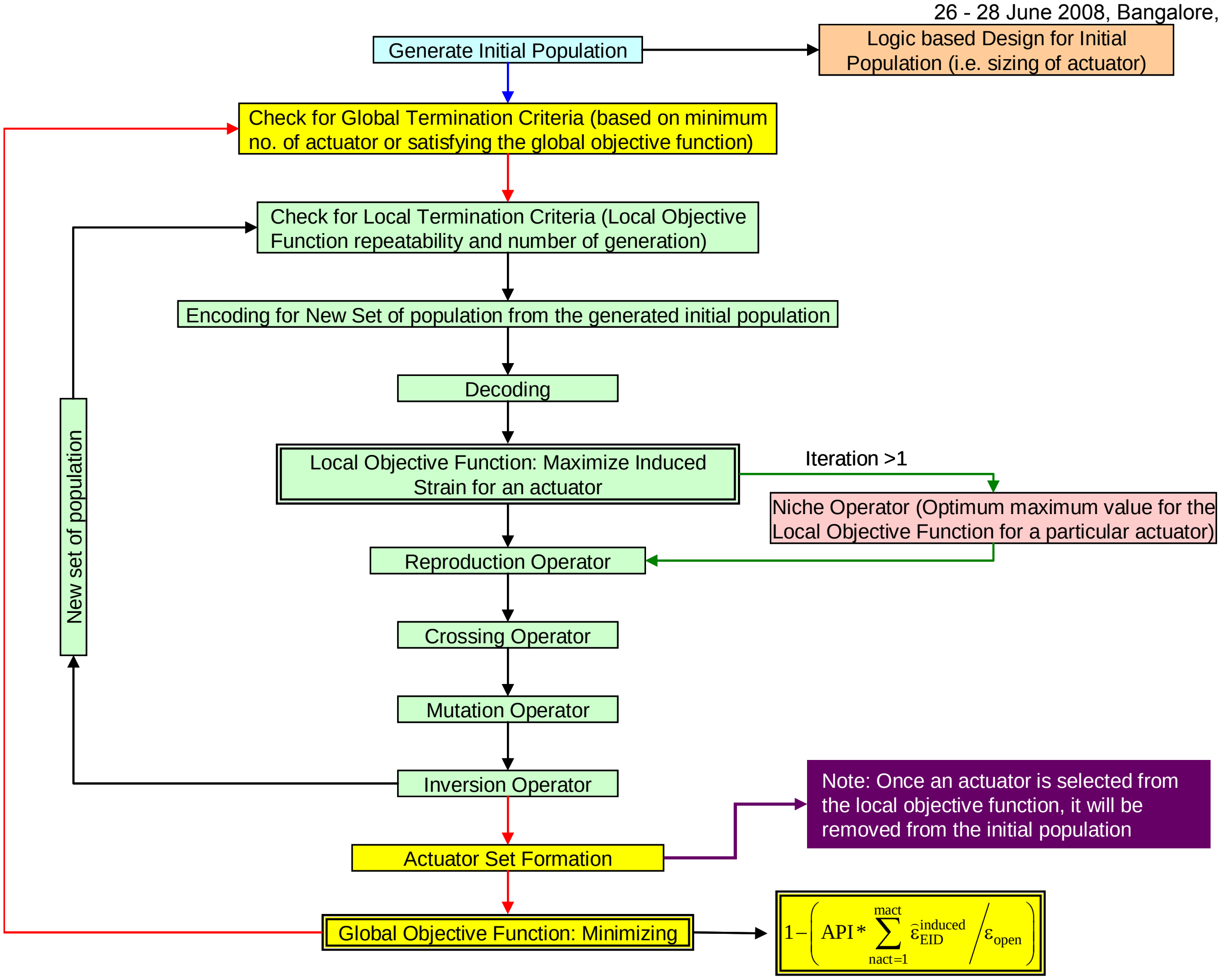


Figure 2: Flow chart for micro-GA based statistical optimization procedure with multiple objective functions

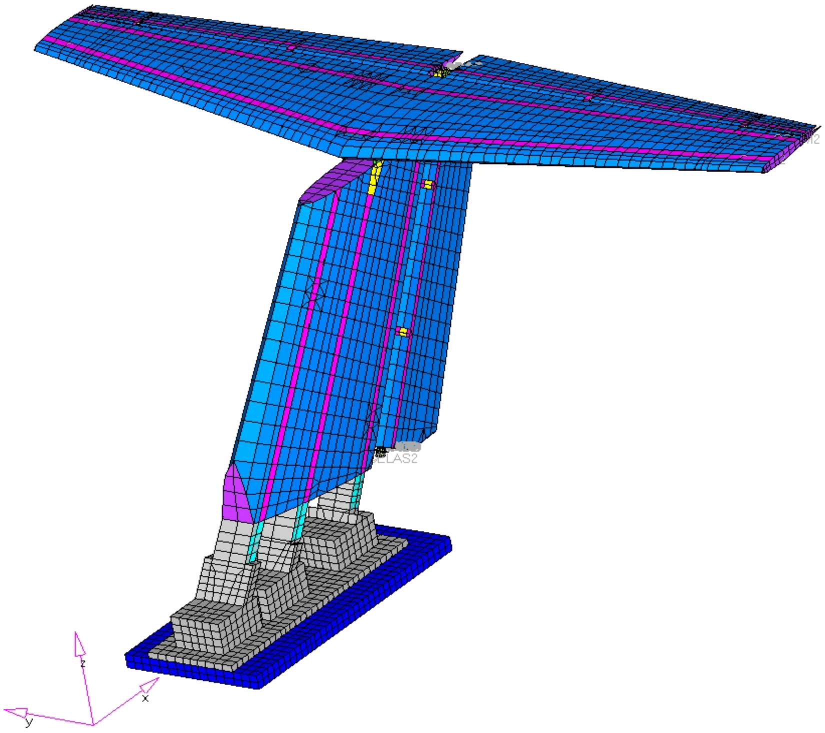


Figure 3a: T-Tail model for actuator and sensor location

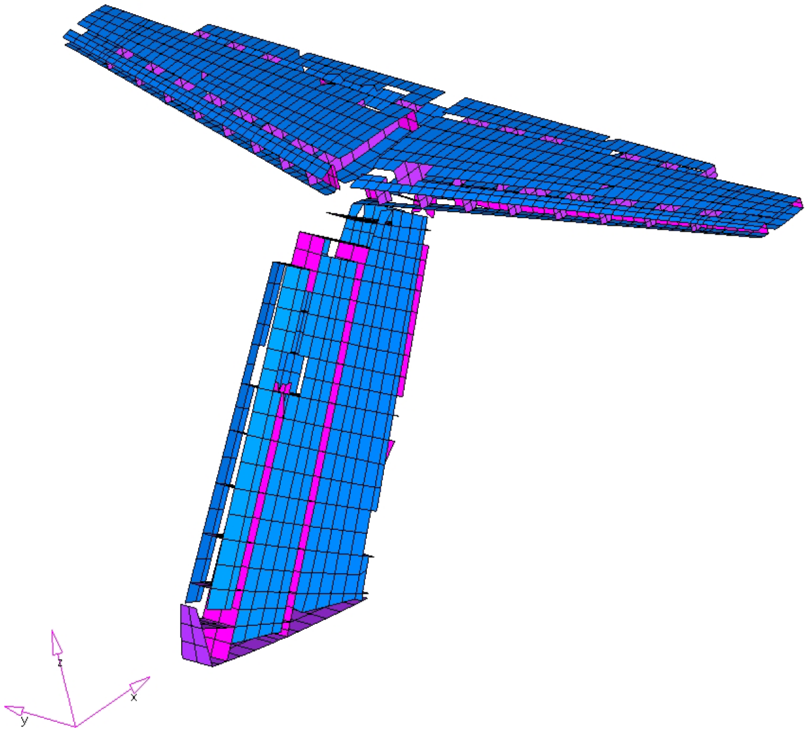
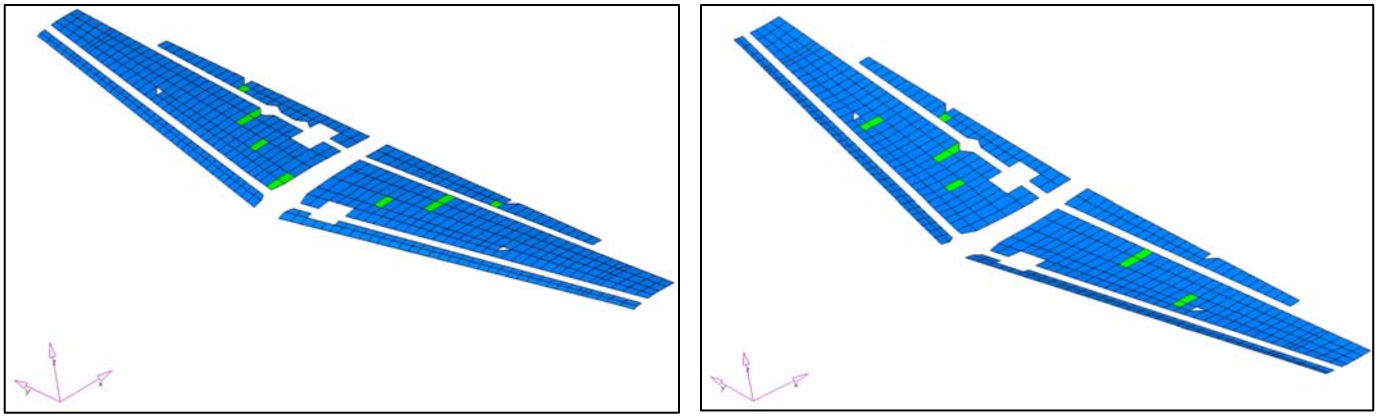


Figure 3b: Reduced T-Tail model for actuator and sensor location



Top skin *Bottom skin*

Figure 4: Locations to place 20 patches for both HT antisymmetric and HT symmetric mode

Table 1: Location and induced strain of 20 actuators for both HT antisymmetric and HT symmetric mode

SLNO.	**Element No.**	**CG of the Element**			**Induced Strain**		**Induced Strain Summation**
		X(mm)	Y(mm)	Z(mm)	Mode1(Anti-HT)	Mode2(Sym-HT)	
1.	7701	171.02	192.062	5.785	0.7537	0.8302	1.5839
2.	6510	170.218	192.047	5.838	0.7615	0.8109	1.5724
3.	6637	132.336	322.422	4.445	0.6275	0.9192	1.5467
4.	6986	175.678	-191.96	6.096	0.7332	0.8044	1.5376
5.	7287	176.267	-191.99	6.045	0.7292	0.8069	1.5361
6.	6747	209.09	256.92	7.208	0.9103	0.6095	1.5198
7.	6843	85.127	31.61	3.07	0.6418	0.8692	1.511
8.	6842	66.276	32.641	2.251	0.8323	0.6688	1.5011
9.	6259	153.182	191.97	5.664	0.6804	0.8108	1.4912
10.	7282	154.229	-191.97	5.07	0.6631	0.8239	1.487
11.	7357	132.538	-322.46	4.9	0.6034	0.8681	1.4715
12.	6160	121.097	127.302	4.268	0.6285	0.8429	1.4714
13.	7466	209.298	-256.82	7.204	0.889	0.5817	1.4707
14.	6468	148.09	322.365	4.9	0.6129	0.8552	1.4681
15.	6459	122.434	127.025	4.21	0.6023	0.8615	1.4638
16.	7190	148.253	-322.2	5.335	0.6102	0.8444	1.4546
17.	6562	154.06	192.29	5.505	0.6581	0.7936	1.4517
18.	6882	121.26	-127.22	4.28	0.6242	0.8273	1.4515
19.	6981	153.182	-191.97	5.22	0.6417	0.8051	1.4468
20.	6755	210.04	256.892	7.365	0.8563	0.5797	1.436

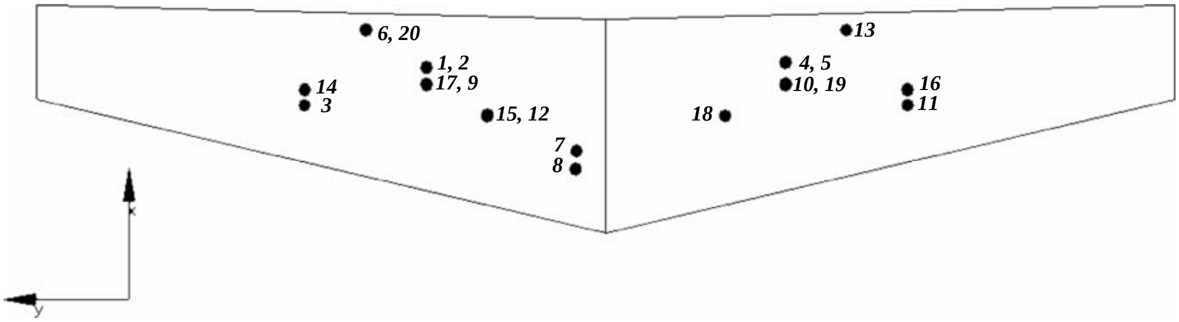


Figure 5: Planform of the 20 patches location for both HT antisymmetric and HT symmetric mode

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