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DIFFERENT DESIGN OF VERTICAL AUXILIARY TABLES AND FLATNESS EVALUATION

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Abstract

The vertical auxiliary table or vibration table is a key component of vibration testing machines to enlarge the test area and transmit required vibration level for different test specifications. The structural stiffness and transmissibility of vibration table is of great concern. This paper lays out the design process and consideration for vibration tables. Different designs of vibration tables are presented base on the respect of top surface flatness for the vibration table under vibration testing conditions. The new design of vibration table is firstly constructed in CAD software and transferred to finite element code to build up its finite element model. Modal analysis and harmonic response analysis are respectively conducted to obtain modal parameters and frequency response functions (FRFs) that are used to determine the flatness index so as to evaluate the table design. Flatness performance index for the vibration table is introduced and used to evaluate different designs of vibration tables. Results show that proper design of table structures can suitably accommodate the vibration response and result in better flatness performance. The modal characteristics of different designs are discussed and revealed important phenomenon for design consideration. This work addresses the design methodology and presents an effective new design of vibration table.

1. INTRODUCTION

Vibration test is one of important environmental tests. A typical vibration test machine is used to conduct such a test. The major components of the vibration test machine contains vibration table attached to the shaker, control unit and sensing device for the implement of feedback control. The control sensor is mounted on the table and as the feedback to control unit. The shaker can then be excited to vibrate according to the control sensing response to meet the specified test spectrum. The general requirements of vibration table can be as follows: (1) enough rigidity to transmit the vibration level from the shaker to the table surface, (2) the surface response on the table being as the same as at the control sensor location, i.e. the flatness of the table, (3) the frequency response being controllable provided the control unit ability. Therefore, the proper design of the vibration table is required to fit the need of vibration testing to accommodate the DUT (device under test).

Finite element analysis (FEA) and experimental modal analysis (EMA) have been widely combined and applied to solve engineering problems [1, 2]. Through the modal testing to obtain the modal data of a real structure, the FE model can be updated for further analysis. Regarding to the vibration table design, there are few if any in the literature. The most pioneer work might be the author's research team. Wang and Chen [3] firstly performed the model verification for vertical auxiliary table in free boundary and then validated the table in mounted condition in practical testing [4]. Wang *et al.* [5] studied a special type of rib-reinforced vibration table to validate its FE model via EMA.

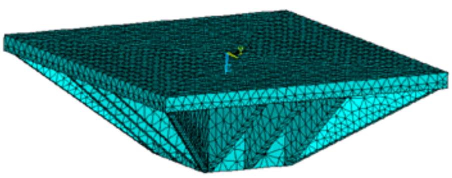
In order to evaluate the vibration table performance in real vibration tests, Wang *et al.* [6] showed the flatness performance index (PI) to quantify the table design. This work will generally adopt this PI definition to evaluate different types of table design. Also, Wang *et al.* [7] proposed a procedure for the auxiliary table design and useful for practical applications. This work integrates the previous research experiences and adopts FEA to virtually design the vibration table, in particular, considering the table flatness during vibration testing.

The design consideration for the vibration table is complex. There are lots of factors to be considered. This work will first layout the evaluation process for the analysis of vibration table and conduct both the analytical and experimental works to characterize the performance of vibration table. Section 2 mainly shows the design evaluation process and presents the performance evaluation for the initial design of the vibration table. Section 3 presents the design modification of the vibration table for several practical concerns in order to seek for a better design of table in terms of flatness performance. Section 4 shows the comparison of different designs and comes out the best one.

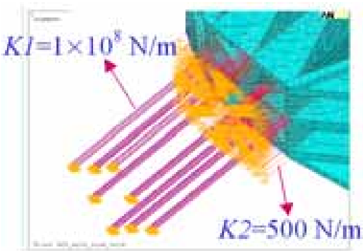
2. PERFORMANCE EVALUATION OF INITIAL DESIGN

The design analysis procedure for the vibration table has been developed [7]. The steps for the design evaluation are discussed as follows:

1. Free Boundary Model Verification: The initial design of the auxiliary table is performed by both FEA and EMA, respectively. Base on the modal parameters comparison, the FE model in free boundary can be validated. The material properties can be properly justified according to experiments. Figure 1(a) shows the finite element model of the table for free boundary. Table 1(a) summarizes the model verification results and reveals reasonable mathematical modelling of the table.
2. Fixed Boundary Model Verification: The vibration table is attached to the shaker on the vibration testing machine as in practical test condition. Both FEA and EMA are also performed, respectively, for the table in fixed boundary condition. The fixed boundary is simulated by applying spring elements at the junctions as shown in Figure 1(b). Spring constants can be well calibrated for the vibration testing machine. Table 1(b) summarizes the model verification results for fixed boundary and reveals good agreement.
3. Auxiliary Table Performance Evaluation: From the validated fixed boundary table model, the flatness performance index (PI) can be defined and evaluated by both FEA and experiments. Upon the comparison of PIs between analysis and experiments. The PI of initial design table can be obtained and used as the reference specification. Table 1(c)



(a) free boundary



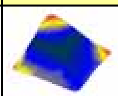
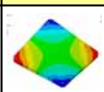
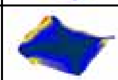
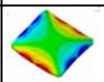
(b) fixed boundary

Figure 1. Finite element model for free and fixed boundary conditions

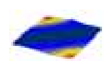
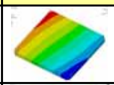
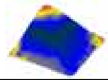
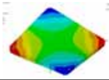
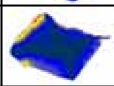
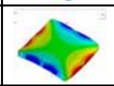
shows both PI_{avg} and PI_{diff} for different locations of control sensors. The smaller of both indices, the better flatness performance for the vibration table.

Table 1. Model verification results and flatness performance evaluation

(a) Free boundary model verification [7]

EMA			FEA			Diff (%)	MAC
mode	Fn (Hz)	mode shape	mode	Fn (Hz)	mode shape		
E-01	978		F-07	1022		4.29	0.97
E-02	1183		F-08	1290		9.32	0.88

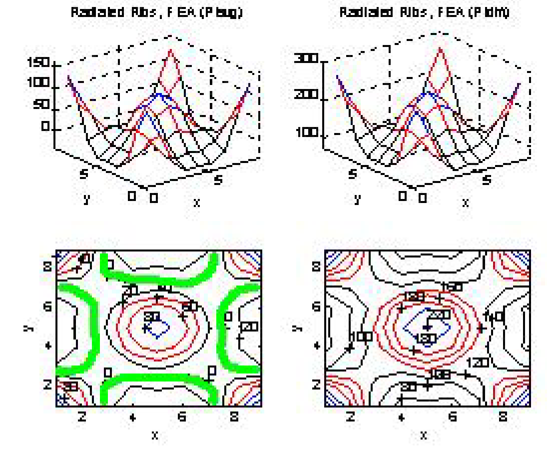
(b) Fixed boundary model verification [7]

EMA			FEA			Diff (%)	MAC
mode	Fn (Hz)	mode shape	mode	Fn (Hz)	mode shape		
E-03	446.2		F-04	439.8		-1.59	0.29
			F-05	442		-0.89	0.68
E-04	978		F-07	1030		4.18	0.97
E-05	1183		F-08	1296		9.92	0.97

(c) Flatness performance index

PI_{avg}				
avg	max	min	std	rms
13.51	120.27	-39.15	42.33	44.18

PI_{diff}				
avg	max	min	std	rms
133.29	258.85	71.44	49.74	142.16



3. DESIGN MODIFICATION WITH ASPECT TO FLATNESS PERFORMANCE

It is noted that the target vibration table is intended to be used in the frequency range up to 500 Hz. At the first glance, the design for the table which fundamental natural frequency should be larger than the operation frequency range to avoid undesirable resonant response is of interest. The next consideration is that the expected response on the top surface of table should be as flat as possible over the operational frequency during vibration testing. From the above consideration, the design process for new structural design can be justified accordingly.

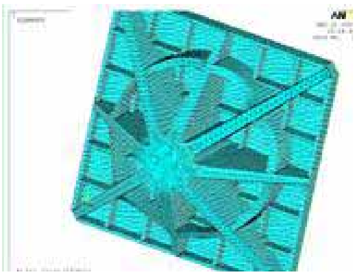
The auxiliary table can be required for different sizes of test surface and so forth the height, thickness, rib shape and else geometry should be properly designed to ensure the proper performance in vibration testing. The optimization problem can be formulated and verbally stated as follows:

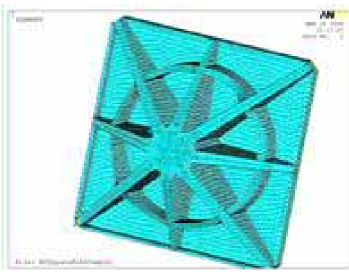
1. Objective Function: This work suggests choosing the distribution of PI_{avg} as shown in Table 1(c) as the objective function to be as small as possible. Consequently, the PI_{avg} and PI_{diff} surfaces for the new design are flattest.
2. Design Variables: There are two phases of new design consideration. Phase I: the geometry design is focused on new shape or different layout of ribs for example. Phase II: the dimension optimization for the selected geometry, such as the height or thickness. This work will primarily focus on Phase I analysis.
3. Constraints: The top and bottom surfaces of vibration table remain unchanged to provide the same test area and to fit the shaker size, respectively. The new design should be as light

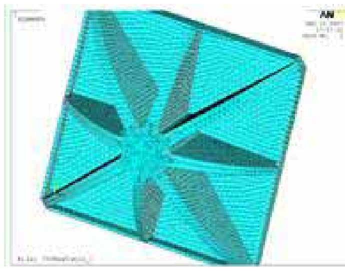
as possible to be no heavier than the initial one. The new design must be manufacturable as well as suitable to fit the coil structures.

For geometry design consideration, some design cases are shown in Figure 2. The evaluations are conducted and summarized as follows:

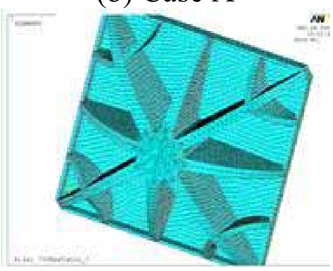
1. Case A: The square ribs appeared in the initial design are removed and studied to evaluate their effects on the flatness of the performance index.
2. Case B: Table 2 shows the static deflection comparison results for a single side rib. The curve-shape rib can reduce almost half of the vertical deformation for the table subject to uniformly distributed force on the top surface than the straight-line rib. Therefore, the major side ribs are modified to be curved shapes. Also, the rounded ribs are removed.
3. Case C: By examining the vertical deflection distribution of the vibration table for Case B as shown in Table 2, a curve rib around four corners can be added to increase the corner stiffness.
4. Case D: The curve ribs in Case C are modified to raise their heights to further increase the corner stiffness.
5. Case E: Since the corner deflection dominates the top surface deflection, the curve ribs to be added along the four sides are also considered.


(a) Initial design


(b) Case A


(c) Case B


(d) Case C


(e) Case D

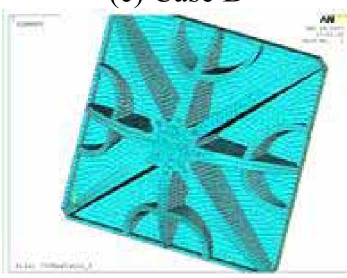
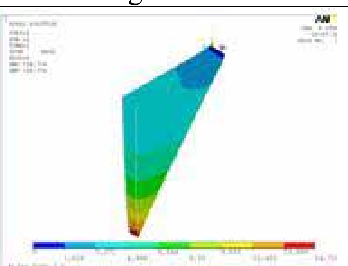
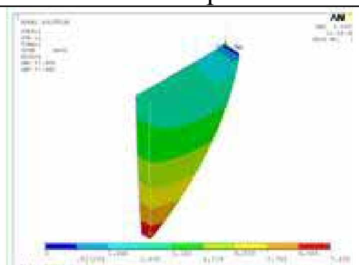
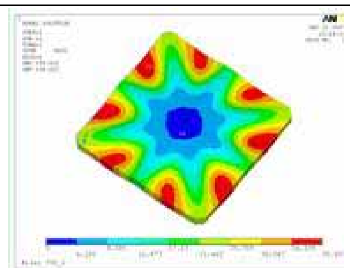

(f) Case E

Figure 2. FE models of all design cases

Table 2. Static analysis for different shapes of ribs

Initial design: Straight-line rib	Case B: Curve-shape rib	Vertical deflection distribution for Case B
		
$\delta_{z,\max}$ =14.724 (mm)	$\delta_{z,\max}$ =7.408 (mm)	$\delta_{z,\max}$ =38.632 (mm)

It is noted that there are many more design options. In this work, the typical cases of design consideration are shown to discuss their effects on the flatness evaluation for the vibration table. Next section will compare their vibration characteristics as well as their flatness performance indices.

Table 3. Modal parameter comparison for the initial and new designs at fixed boundary

Initial Design		Case A		Case B		Case C		Case D		Case E	
mode f_n (Hz)	Mode shape	mode f_n (Hz)	Mode shape	mode f_n (Hz)	Mode shape	mode f_n (Hz)	Mode shape	mode f_n (Hz)	Mode shape	mode f_n (Hz)	Mode shape
F-04		**F-04**		**F-04**		**F-04**		**F-04**		**F-04**	
438.39		**454.43**		**446.13**		**432.25**		**416.47**		**419.08**	
F-05		**F-05**		**F-05**		**F-05**		**F-05**		**F-05**	
441.34		**456.79**		**446.93**		**433.51**		**417.16**		**422.03**	
F-06		**F-06**		F-06		F-06		F-06		F-06	
1030		**1051**		820.36		850.42		820.27		861.59	
F-07		**F-07**		F-07		F-07		F-07		F-07	
1074		**1089**		842.64		863.73		838.50		867.24	
F-08		F-08		F-08		F-08		F-08		F-08	
1296		1277		843.49		864.81		840.96		870.40	
F-09		F-09		F-09		F-09		F-09		F-09	
1458		1401		863.80		880.30		871.20		905.81	
F-10		F-10		**F-10**		**F-10**		**F-10**		**F-10**	
1468		1407		**1057.6**		**1025.1**		**980.76**		**1052.0**	
F-11		F-11		**F-11**		**F-11**		**F-11**		F-11	
1667		1514		**1114.1**		**1079.3**		**1036.6**		1070.7	
F-12		F-12		F-12		F-12		F-12		**F-12**	
1779		1718		1117.3		1135.6		1189.8		**1126.7**	
F-13		F-13		F-13		F-13		F-13		F-13	
1780		1740		1390.5		1444.0		1446.4		1259.2	
F-14		F-14		F-14		F-14		F-14		F-14	
1782		1742		1415.7		1466.1		1464.7		1260.1	
F-15		F-15		F-15		F-15		F-15		F-15	
1883		1901		1434.1		1539.0		1561.8		1350.4	

4. COMPARISON OF NEW DESIGNS

Table 3 shows the natural frequencies and corresponding mode shapes for different designs of vibration tables. Some observations are discussed as follows:

1. For the initial design of vibration, there are two resonant frequencies below 500Hz, i.e. F-04 and F-05 that are symmetric modes and revealed near (2,1) mode vibrating the same phase for four corners from experiments as shown in Table 1(b). The next resonance appears above 1000Hz. In viewing the modal characteristics, the initial design roughly meet the vibration test criterion in operational frequency 500Hz. The major concern modes can be those F-04 and F-05 modes.
2. For Case A, the modal properties are about the same as the initial design, i.e. the small square ribs help not much stiffness regarding to the modal response in the interested frequency ranges.
3. For Case B, the F-04 and F-05 modes are slightly increased in comparison to the initial one. However, there are several modes appear between 500Hz and 1000Hz. These modal characteristics might not be proper for the specified vibration test criterion for those modes contributing their modal response to lower frequency range.
4. For other Cases of new design, there appear quite similar modal properties with Case B only that the modal sequence could be slightly changed. Basically, those particular modal frequencies can be raised due to different setups of ribs. In particular for the F-06 and

F-07 modes, the modal frequencies are slightly increased for most new designs. This may increase the surface flatness in practical vibration testing.

For the study of the flatness performance of table design, two phases of studies are shown in this paper. First, the control sensor is assumed to be applied at the corner of the vibration table. Table 4 shows the flatness distributions over the top surface of the vibration table. It is noted that PI_{avg} is the mean of error percentages of difference at the measured point from the control sensor location. PI_{diff} is the difference between the maximum and minimum errors, i.e. $\mathrm{PI}_{diff} = \varepsilon_{\max} - \varepsilon_{\min}$. Through the PIs, one can visualize the flatness of the vibration table in the testing condition. Some observations are discussed as follows:

1. The initial design reveals zero errors in comparison to the specified testing spectrum at four corners for the effect of control sensor location. However, other areas appear large difference from the objective response for PI_{avg} =120 and PI_{diff} =258.85.
2. As one can observe that all other Design Cases also reveal the zero errors at four corners. The PI_{avg} and PI_{diff} values are much smaller in comparison to those of the initial one. In particular, Design Case D has the smallest value of PI_{avg}, while Design Case D has the smallest value of PI_{diff}.
3. From the comparison, one can observe that all of the new designs reveal better flatness performance indices than those of the initial one for the control sensor at the corner location. The thicker lines indicate the surface response with zero errors, i.e. complying with the specified vibration test spectrum.

Table 4. PIs comparisons for different design cases for the control sensor at corner location

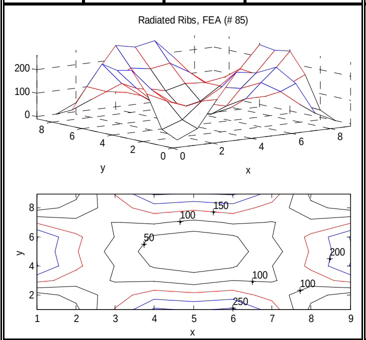
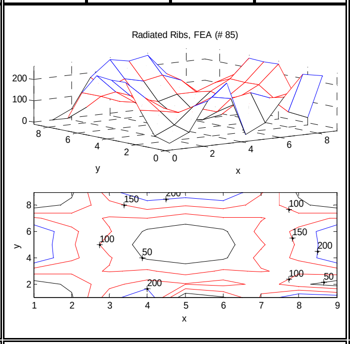
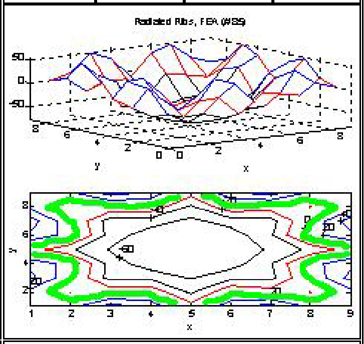
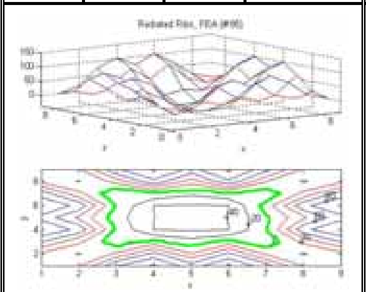
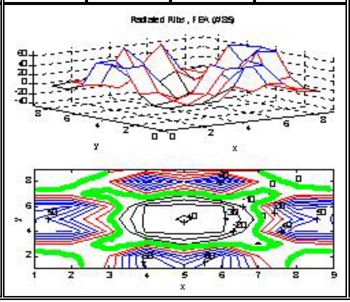
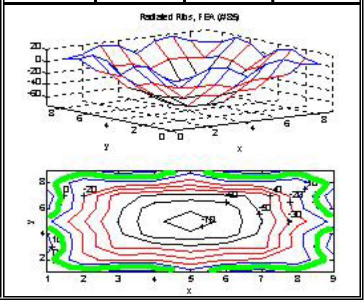
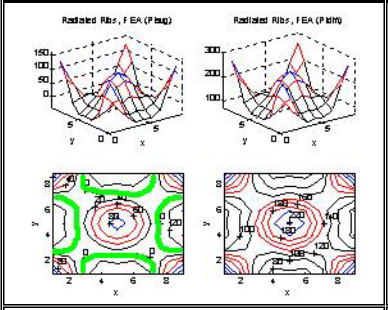
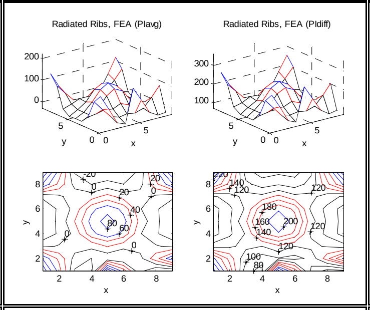
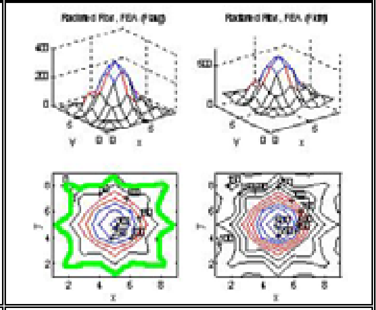
Initial design				Case A				Case B			
PI_{avg}	PI_{diff}	ε_{max}	ε_{min}	PI_{avg}	PI_{diff}	ε_{max}	ε_{min}	PI_{avg}	PI_{diff}	ε_{max}	ε_{min}
120.27	258.85	258.85	6.94×10^{-17}	117.81	251.16	251.06	-0.1007	-12.29	129.69	51.19	-78.51
											
Case C				Case D				Case E			
PI_{avg}	PI_{diff}	ε_{max}	ε_{min}	PI_{avg}	PI_{diff}	ε_{max}	ε_{min}	PI_{avg}	PI_{diff}	ε_{max}	ε_{min}
27.52	152.36	103.92	-48.44	11.35	107.74	66.08	-41.66	107.74	66.08	-41.66	-19.95
											

Table 5. Overall flatness distributions over the test surface for different control sensor locations

Initial design					Case **A**					Case **B**				
PI_{avg}					PI_{avg}					PI_{avg}				
avg	max	min	std	rms	avg	max	min	std	rms	avg	max	min	std	rms
13.51	120.27	-39.15	42.33	44.18	13.41	118.16	-38.12	42.34	44.16	33.76	317.74	-42.10	88.17	93.91
PI_{diff}					PI_{diff}					PI_{diff}				
avg	max	min	std	rms	avg	max	min	std	rms	avg	max	min	std	rms
133.29	258.85	71.44	49.74	142.16	129.68	251.57	70.62	48.77	138.45	197.78	617.65	85.60	130.37	236.44

Case **C**					Case **D**					Case **E**				
PI_{avg}					PI_{avg}					PI_{avg}				
avg	max	min	std	rms	avg	max	min	std	rms	max	max	min	std	rms
14.66	150.66	-37.81	46.25	48.25	7.56	92.02	-33.04	29.38	30.16	18.57	212.03	-31.63	58.87	61.38
PI_{diff}					PI_{diff}									
avg	max	min	std	rms	avg	max	min	std	rms	max	max	min	std	rms
136.95	299.27	74.25	55.23	147.54	104.03	185.58	64.72	28.41	107.79	134.58	354.14	77.61	66.82	150.07

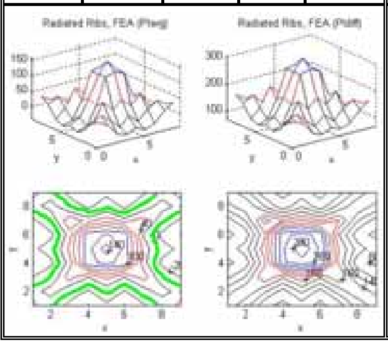
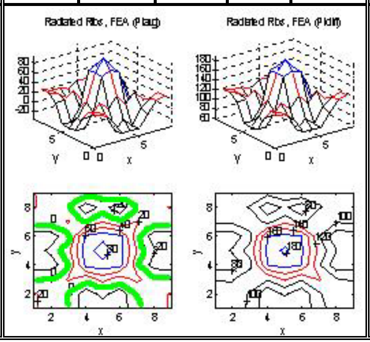
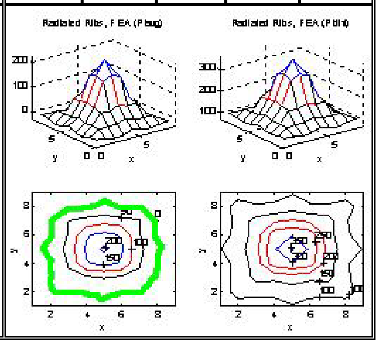




Table 6. PIs comparison for different design cases

(a) PI_{avg}

Case	PI_{avg}(%)		Difference (%)	
	avg	rms	avg	rms
Initial	**13.51**	**44.18**	-	-
Case A	13.41	44.16	-0.1	-0.02
Case B	33.76	93.91	+20.25	+49.73
Case C	14.66	48.25	+1.15	+4.07
Case D	**7.56**	**30.16**	**-5.95**	**-14.02**
Case E	18.57	61.38	+5.06	+17.20

(b) PI_{diff}

Case	PI_{diff} (%)		Difference (%)	
	avg	rms	avg	rms
Initial	**133.29**	**142.16**	-	-
Case A	129.68	138.45	-3.61	-3.71
Case B	197.78	236.44	+64.49	+94.28
Case C	136.95	147.54	+3.66	+5.38
Case D	**104.03**	**107.79**	**-29.26**	**-34.37**
Case E	134.58	150.07	+1.29	+7.91

The second phase of study is to evaluate the flatness performance considering different control sensor locations all over the top surface of the vibration table. Tables 5 and 6 show the comparisons between the initial design and other Design Cases, respectively. There are two figures for each Design Case in Table 5. They are PI_{avg} and PI_{diff} distribution plots for choosing different locations of control sensors. Some discussions are as follows:

1. The thicker lines in PI_{avg} plots represent the PI_{avg} =0, i.e. the average of flatness index is zero, where the control sensor is applied. One can compare the distributions of thicker lines and observe their different characteristics for flatness evaluation accommodate with the vibration test criterion for their smooth distribution of flatness index.

2. For Design Cases A without the small square ribs in comparison to the initial one, the PIs are nearly the same as the initial one, i.e. the small square ribs can be excessive.
3. For Design Cases C and D, if the control sensors are chosen along the thicker line locations, either the PI_{avg} or PI_{diff} has about the similar performance as those of the initial design.
4. In overall evaluation, from Table 6 one can see that Design Case D has the best flatness performance in terms of both PI_{avg} and PI_{diff} among all cases.

5. CONCLUSIONS

This paper addresses the design modification of vibration table for a vibration test machine in considering the flatness performance for practical application with the effect of control sensor locations. Several design cases are illustrated to show the design concept. Design Case D is the best choice in terms of flatness performance indices by PI_{avg} and PI_{diff} . From the design analysis, the proper location of control sensor can also be provided and important to conduct such a vibration test in practice. The flatness characteristic of vibration table in testing condition can then be predicted and useful for practicing engineers to setup the vibration test to give better flatness of vibration table during testing. This work layouts the design analysis procedure and conducts different design case evaluation by employing this procedure. The new design of vibration table can be obtained and perform better vibration test in terms of flatness performance.

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