CHAPTER 4

RESPONSES OF THE PARTIALLY LAMINATED PIEZOELECTRIC STATOR

In this chapter, dynamic behavior and harmonic characteristics of the piezoelectric arc stator system are evaluated by using the analytical and finite element methods. Natural frequencies of the system are presented, followed by forced harmonic responses and wave propagation characteristics at the operating frequencies.

4.1. Natural Frequencies

Table 4.1 shows natural frequencies of the arc stator bonded with piezoelectric actuators configured as Patterns 1 and 2 as previously discussed. Analytical results give the same natural frequencies for both actuator patterns because the approximation of the composite laminate estimates the overall structural stiffness related to the actuator area and these two patterns have the same total area of actuators, regardless the specific actual locations. However, FE results show that the arc stator systems of Patterns 1 ad 2 have slightly different natural frequencies, in which the actuator locations are considered. The actuator patch increases the local stiffness of the stator where it is located. Thus, the arc stators with different actuator patterns yield different system stiffness and natural frequencies.

Comparing the analytical data (simply support) and the FE results (simply support) shows that the natural frequencies are compared well. This implies that the analytical and FE methods are valid since solutions of the two methods are closed when they have the same boundary condition. Then, the boundary condition of the arc stator is modified in order to represent the physical model because, in practice, it is difficult to implement the ideal simply support boundary condition. Details of modified-simply boundary condition have been previously discussed in [14]. That is, nodal displacements of boundary nodes at ϕ = 0 and $\pi/2$ in the ϕ-direction are zero and nodal displacements of stator's mid-span at ϕ = 0 and $\pi/2$ in the 3-direction are zero. At the same vibration mode, the FE result (modified support) also shows higher natural frequency than the analytical result, due to their localized effects and boundary conditions. In general, natural frequencies of Pattern 2 are higher than those of Pattern 1 in FE results (modified support), due to additional actuator stiffness near the boundary supports, except those modes with peaks and/or wave-lengths located near the mid-span, e.g., the 5^{th} mode.

Table 4.1. The natural frequencies of the arc stators with various actuator patterns.

Mode (k)	Natural Frequencies (Hz)					
	Analytical Result (Simply support)		FE Result (Simply support)		FE Result (Modified support)	
	Pattern 1	Pattern 2	Pattern 1	Pattern 2	Pattern 1	Pattern 2
2	1058	1058	937	1149	1532	1649
3	2491	2491	2419	2566	2996	3254
4	4733	4733	4768	4799	5966	5841
5	7392	7392	7531	7196	8592	8176
6	10879	10879	11235	10957	12714	12511
7	14765	14765	15387	15441	17451	17339
8	19488	19488	19674	19745	21487	21707
9	24602	24602	25357	25540	27850	27953
10	30556	30556	31252	31784	33883	34672
11	36899	36899	37797	37941	40327	40910

There are two reasons that the analytical and FE results (modified support) of natural frequencies are not very closed. First, in the "theoretical" estimation, the assumption of composite laminar represents the averaged macroscopic effect of the structure [20, 21]. Based on the approximated formulations in mass and area moment of inertia, the added mass and stiffness of partially laminated actuators are assumed uniformly distributed over the arc structure. This doesn't represent the local effect of partially laminated piezoelectric arc structure because the actuators are not fully and uniformly laminated on structure as the assumption was developed. Second, their boundary conditions are slightly different. In the analytical calculation, it is assumed that the boundary conditions are simply supports and the system equations are developed and the solution has been firstly obtained accordingly [19]. Though, the presented FE results are based on the modified-simply support boundary conditions in order to mimic the experimental boundary conditions. The FE results (modified support) are expected to predict experimental results, while analytical estimations serve as reference. Due to the approximated averaged assumption stated above, they are supposed to be lower than the FE results (modified support), as indicated in the table.

The analytical results of natural frequencies of partially laminated piezoelectric arc stator are still good estimation since they are all lower than those of fully laminated piezoelectric arc stator, due to the first reason [14]. This implies that the conventional lamination approximation doesn't represent the partially laminated arc structure well; the "uniformly distributed" calculations underestimate the system stiffness and boundary condition effect. Even though the analytical and FE results of natural frequencies of the partially laminated piezoelectric arc stator are different due to their different fundamental estimations, they still generate similar wave characteristics when the system is excited at selected natural frequencies and specified operating frequencies as shown in the presented results.

4.2. HARMONIC RESPONSES

Frequency responses of the piezoelectric arc stator system with two actuator patterns, mentioned previously, are investigated. The piezoelectric actuator patches are subjected to sinusoidal electrical excitations with an amplitude of 10V and the top and bottom piezoelectric actuators are respectively excited by the signals of $10\cos(\omega t)$ and $10\sin(\omega t)$. The excitation frequency ω is varied from 0 to 60,000 Hz. Harmonic response of the piezoelectric arc stator systems is investigated using the FE method. The transverse displacement of the mid-span node, i.e., the angle position of $\pi/4$, is presented. Figures 5 and 6 show the frequency responses of the arc stator bonded with the piezoelectric actuators designated as Patterns 1 and 2, respectively. It is observed that the transverse displacement of the mid-span node is large when the system excited in the neighborhood of the natural frequencies. Comparing Figures 5 and 6 within the same anti-resonance frequency suggests that the vibration amplitude of the stator bonded with the actuators near the supports (Pattern 2) is higher than that of the stator bonded with the actuators set on the mid-span (Pattern 1). The reason for this is that the partially laminated arc stator with piezoelectric patches near the supports allows more flexibility than the middle span pattern.

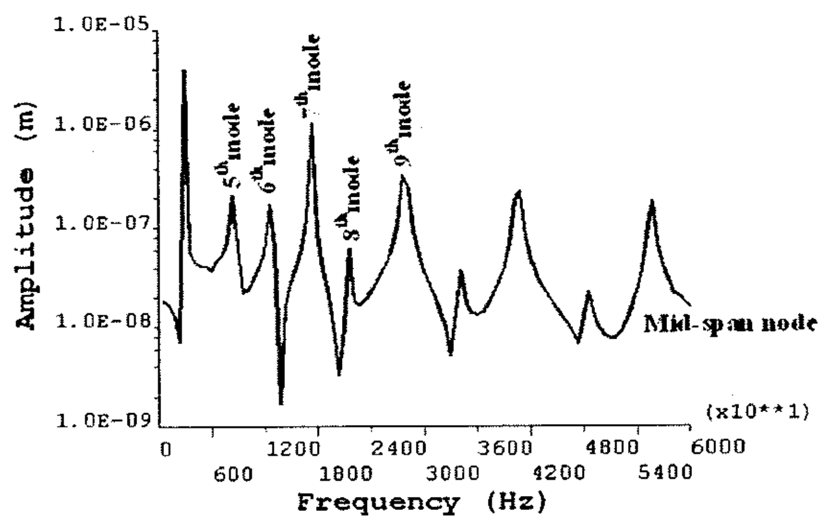

Figure 4.1. Harmonic response of the arc stator with the actuators in the middle of the arc span (Pattern 1).

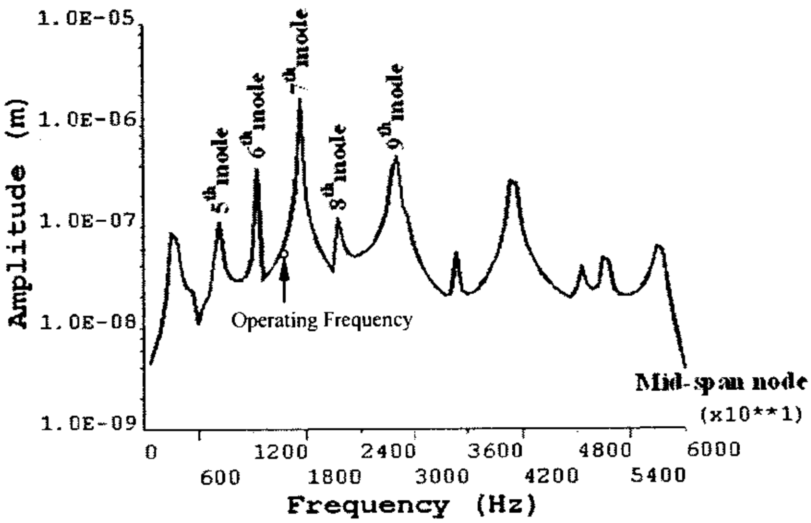

Figure 4.2. Harmonic response of the arc stator with the actuators near the supports (Pattern 2).

However, these harmonic frequency responses do not reveal the operating frequency that generates the traveling wave. Thus, variation of the arc stator deformation in time is investigated to determine the traveling wave.

4.3. WAVE PROPAGATION

As discussed previously, a generated wave is a combination of standing and traveling waves driven at a selected frequency, which can be used to effectively drive the motor in the curvilinear motor system. The change of the arc stator deformation in time represents the wave propagation behavior on the arc stator. Based on the analytical calculation, the arc stator system with the piezoelectric actuators set in the middle span (Pattern 1) is unable to generate effective traveling wave within the frequency range of 0-60,000 Hz. Figure 4.3 shows the response of the arc system configured as Pattern 1 driven at the frequency of 13,460 Hz, in which the amplitude is plotted with respect to angular location of the arc. The arrow on the peak indicates a specific transverse wave u_3 plotted at three time instants (from top to bottom), while the circumferential wave response is denoted by u_ϕ. Note that the wave amplitude dramatically decreases after passing the mid-span (45°) indicated in abscissa.

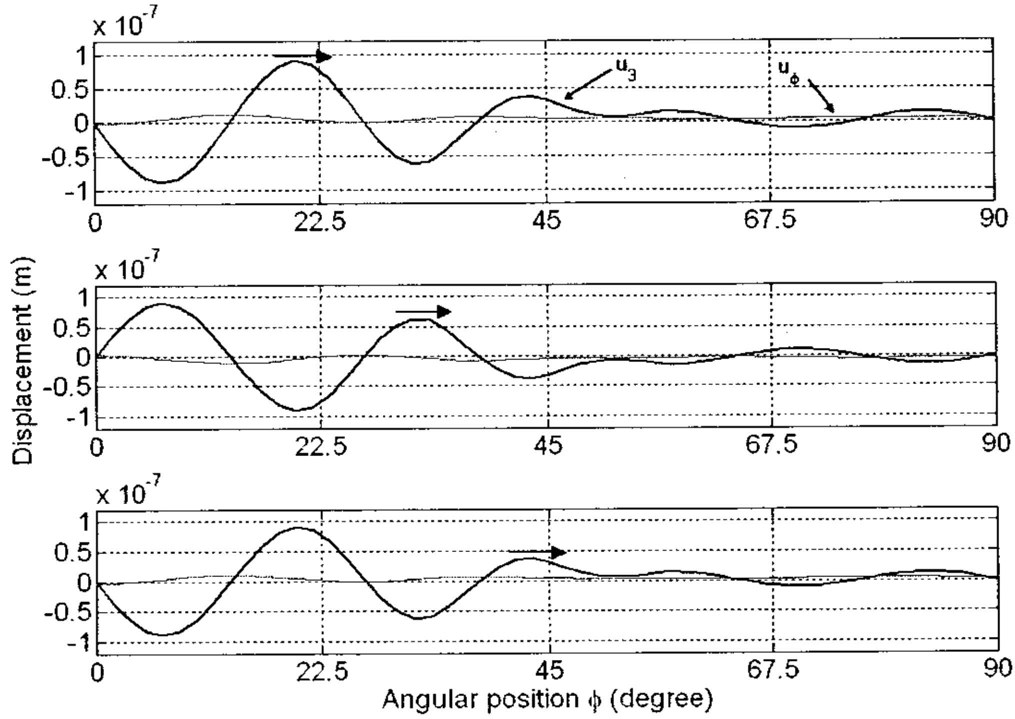

Figure 4.3. Analytical result of the arc stator with the actuators in the middle span (Pattern 1) at the frequency of 13,460 Hz. (u_3: Transverse displacement; u_ϕ: Circumferential displacement.)

However, for the arc stator with the piezoelectric actuators placed near the supports (Pattern 2), the stator system driven at 12,500 Hz generates a rather steady traveling wave, as illustrated in Figure 4.4. The wave travels over the arc with very higher amplitude and less fluctuation, as compared with those generated in Pattern 1. Accordingly, Pattern 2 is a much better actuator/stator configuration than Pattern 1, due to its generated steady traveling wave, i.e., the driving action to the motor.

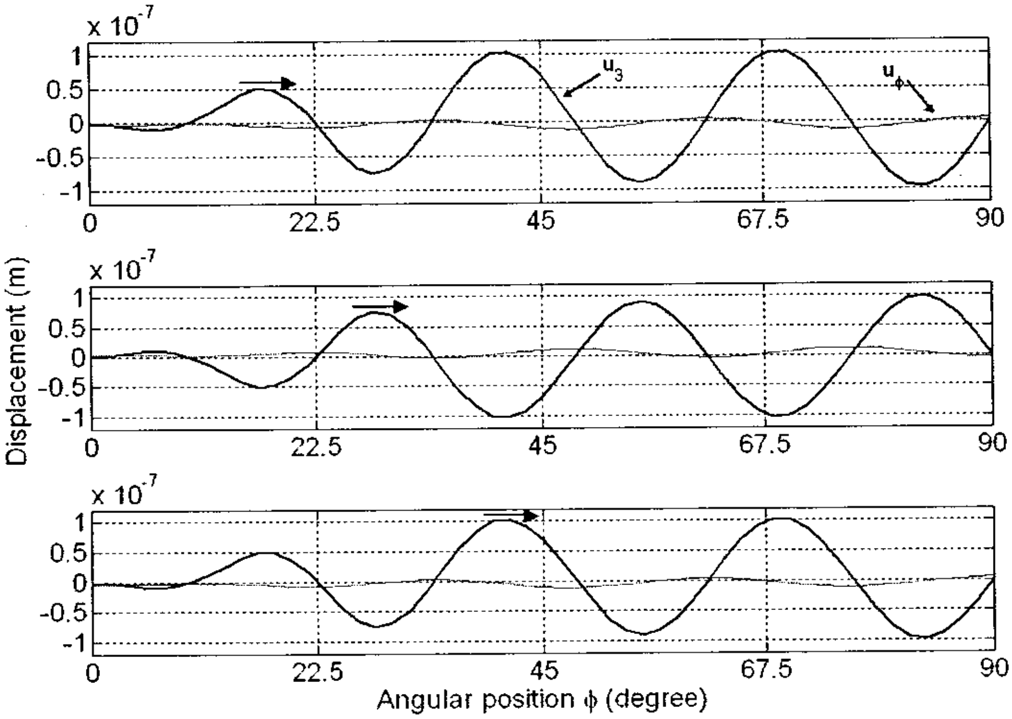

Figure 4.4. The analytical result of the arc stator with the actuators near the supports (Pattern 2) at the operating frequency of 12,500 Hz. (u_3: Transverse displacement; u_ϕ: Circumferential displacement.)

Again, travel wave behaviors of the two actuator patterns are investigated using the FE technique. Figure 4.5 shows the traveling wave responses at three time instants of the arc stator with the mid-span actuators (Pattern 1) at the frequency of 15,020 Hz. The arrow, again, highlights a specific wave traveling on the arc. Figure 4.6 shows the FE response of the arc stator with the actuators placed near the supports (Pattern 2) at 14,320 Hz. Responses of the piezoelectric arc stator systems based on the FE analyses also show the same characteristic as that of the analytical calculations. Accordingly, the arc stator bonded with the mid-span piezoelectric actuators (pattern 1) is unable to generate effective traveling waves (Figure 4.5). On the other hand, the arc stator bonded with the piezoelectric actuators near the supports (Pattern 2) provides much better wave propagations (Figure 4.6). Figure 4.7 illustrates the 6^{th} and 7^{th} mode shapes of the arc stator with the actuators near the supports (Pattern 2). Comparing these mode shapes with the generated traveling wave, it shows that the traveling wave in Figure 4.6 has the wave configuration comparable to a combination of the 6^{th} and 7^{th} modes. And the operating frequency of 14,320 Hz is in between the 6^{th} and 7^{th} modes which are 12,511 and 17,339 Hz, respectively, as shown in Table 4.1.

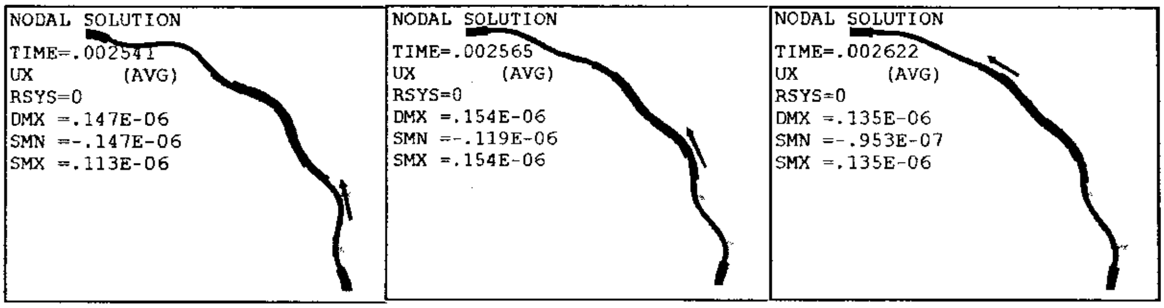

Figure 4.5. The FE result of the arc stator with the actuators in the middle span (Pattern 1) at the frequency of 1,5020 Hz.

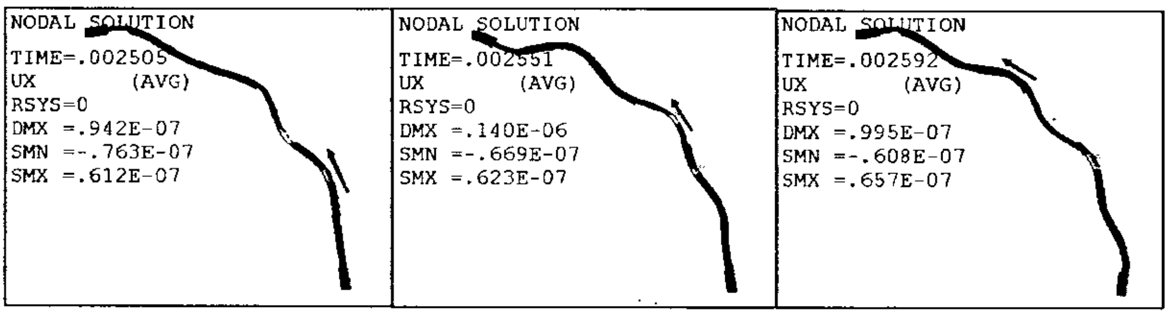

Figure 4.6. The FE result of the arc stator with the actuators near the supports (Pattern 2) at the operating frequency of 14,320 Hz.

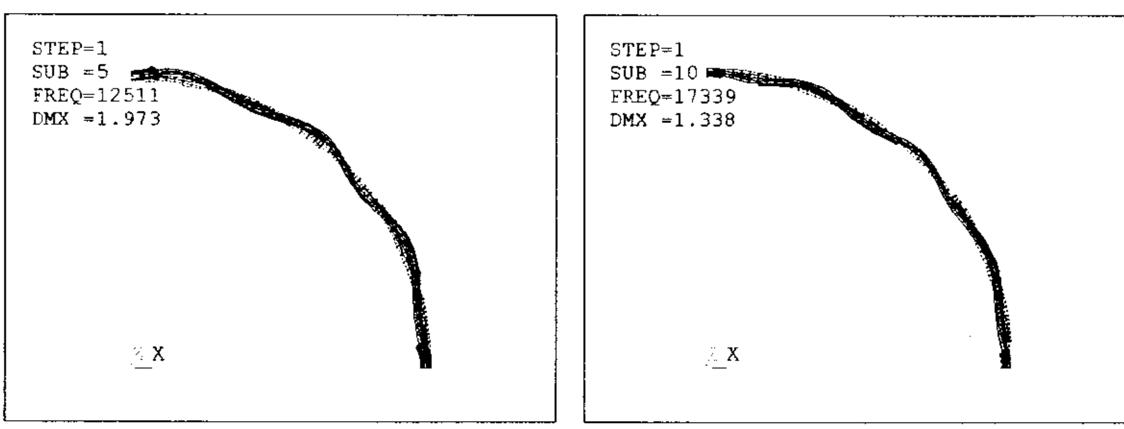

Figure 4.7. The FE results of the 6th and 7th mode shapes of the arc stator with the actuators near the supports (Pattern 2). (Left: the 6th mode; Right: the 7th mode)

The present analytical and FE results indicate that the actuator locations affect both natural frequencies and wave propagations. Note that although operating frequencies and wave amplitudes of the analytical and FE (modified support) results are not exactly the same, due to their fundamental modeling difference, the operating frequencies of these two models are all in between the 6th and 7th modes (Table 4.1) and thus both generate similar wave characteristics.

These two actuator patterns are designed based on the same segmentation technique, i.e., identical size and number of actuator patches. The only difference is the actuator locations placed on the curvilinear stator. Analysis data suggests that the actuators should be located near the supports in order to guarantee an effective traveling wave response. Consequently, this study demonstrates that the stator/motor system, although with less actuator patches, can still generate effective traveling waves driving the motor.