Mechanical Modes of Multicell Linac Structures

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ABSTRACT

Mechanical vibrations in an electron linac structure can lead to growth of the longitudinal and transverse phase space of the accelerated beam. Such degradation of the electron beam is not prevented by RF stabilization of the accelerating fields. We have made measurements of the lowest frequency mechanical modes for several important linac structures, including the 4-cell CERN structure as modified by DESY, and the original 7-cell Stanford structure. The structures used in this study were fabricated for operation at 1300 Mhz. The issues discussed in this paper are particularly important for electron linac applications where pointing stability, position stability, and electron beam energy stability are crucial.

1. INTRODUCTION

Acoustic noise can drive the lowest frequency mechanical modes of a linac structure and degrade the longitudinal and transverse phase space of the accelerated beam. As shown elsewhere[1], modulation of the electron beam will occur despite RF stabilization of the accelerating fields. The low frequency mechanical modes of a multi-cell linac structure can be classified either as longitudinal, transverse, or torsional. Excitations of longitudinal modes will result in modulation of the energy gained by the electron beam, while excitation of transverse modes will result in both a transverse modulation of the electron beam and a modulation of the energy gain. Torsional modes are not expected to affect the electron beam properties. The avoidance of these electron beam modulations is particularly important in electron linac applications where pointing stability, position stability, and electron beam energy stability are crucial.

The amplitude of vibrational motion will depend on the acoustic noise sources in the immediate vicinity of the linac, on the coupling of these noise sources to the linac structure itself, on the likelihood of frequency coincidence between source and structure resonances, and on the damping of the structure mechanical modes. Measurements[2] of ground vibrations at the Stanford superconducting linac are shown in Fig. 1. As seen in the figure, the ground vibration spectrum in the region from 1 Hz to 50 Hz consists of a collection of large spikes superimposed on a broad low level vibrational background. The spectrum of large spikes, in fact, consists of two harmonic series generated by two large reciprocating compressors that are part of the 1.8 K helium refrigerator. The large spike at 47.5 Hz corresponds to a ground motion amplitude of 0.1 µm while the background motion at this frequency corresponds to an amplitude of 2 X 10^{-3} µm. There are many other possible noise sources including, in particular, pressure fluctuations in the liquid helium system.

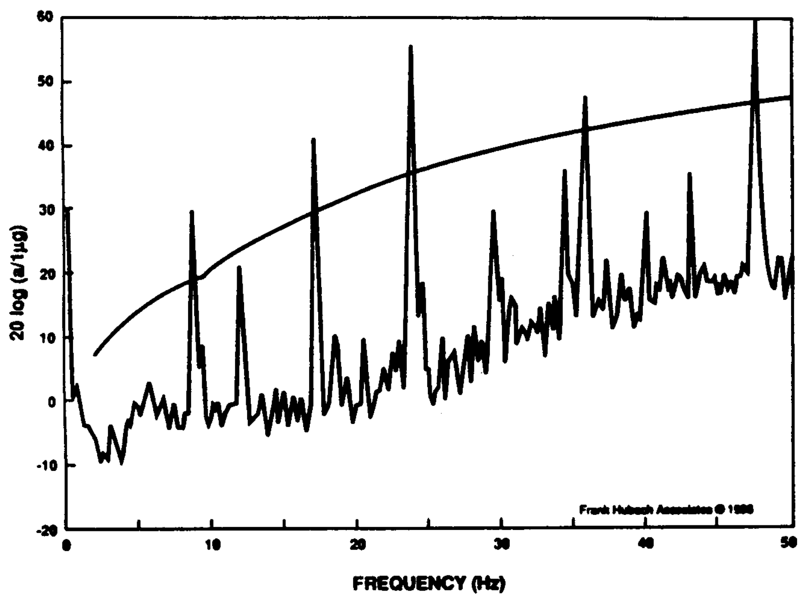

Fig.1 Ground vibrations near the Stanford superconducting linac. The spectrum of large spikes consists of two harmonic series generated by two large reciprocating compressors that are part of the 1.8 K helium refrigerator. Ground motion = $a/(2\pi f)^2$

In a carefully designed system it is always possible to reduce the coupling of acoustic noise sources to the linac structure, and to damp the acoustic vibrations. At Stanford the original linac structure was cradled in the helium dewar by a low frequency support system that provides both isolation and damping. Furthermore, the mechanical mode frequencies of the structure were pushed to higher values by welding longitudinal support rods to the structure, thus moving the structure resonances out of the frequency range where the ground motion amplitude is largest. Some effort was also made to reduce acoustic noise transmission through the RF input, and finally, the decision to operate at superfluid helium temperature minimized pressure fluctuations in the helium bath.

In this paper we present measurements of the lowest frequency mechanical modes for several important linac structures, including the 4-cell CERN structure[3] as modified by DESY[4], and the original 7-cell Stanford structure[5]. The apparatus used in these studies is described in Section 2 of this paper and mechanical mode measurements on the freely suspended structures are presented in Section 3. Since the vibrational mode spectrum will be influenced by the support system and the tuning system employed, several issues related to end constraints are discussed in Section 4. Conclusions are presented in Section 5.

2. MEASUREMENT APPARATUS

The lowest frequency mechanical modes of each structure were measured with both ends of the structure free. Suspending the structure from thin steel wires permitted longitudinal motion, torsional motion, and transverse motion in the horizontal plane to occur unimpeded. Under these conditions, the mode frequencies are not perturbed by the support system and the Q-value ($f\tau$) of the modes is typically 300 or greater. To excite the mechanical modes, an audio oscillator signal was amplified by a Sony portable stereo and the stereo pointed at the structure as shown in Fig. 2. Although the only acoustic coupling to the structures was through the air, the structures were easily driven at any of their lowest modes.

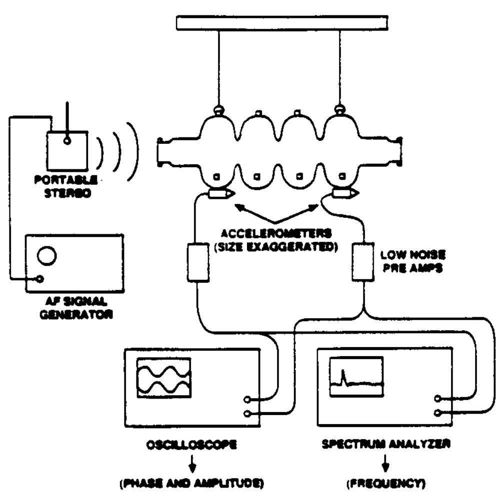

Fig 2. Apparatus for measuring mechanical modes of freely supported accelerator structures.

The mechanical response of the structure was determined using two small PCB 303A02 piezoelectric accelerometers attached with soft wax to different parts of the structure. The signals from these accelerometers were amplified by low noise pre-amps and sent to an HP 35660A spectrum analyzer and an oscilloscope. By sweeping the audio oscillator frequency and observing the amplitude and frequency of the signal on the spectrum analyzer, it was possible to determine the mechanical mode spectrum. In some cases, prior information on the location of the modes was obtained by tapping the structure and observing the resulting spectrum on the spectrum analyzer.

Once the frequency of the lowest resonant modes had been located, each mode was driven individually, and the amplitude and phase of the motion were analyzed. By keeping one accelerometer fixed on an antinode, and moving the other accelerometer to different locations on the surface of the structure the shape of the modes was determined and modes were identified and classified. Modes were classified as longitudinal (n=1,2,3..) , transverse (n=1,2,3...), or torsional.

Difficulties arose occasionally when two or more modes were nearly coincident in frequency, making it difficult to drive them separately. An example of this is seen at 712 Hz in the 4-cell CERN/DESY structure where a longitudinal mode and a transverse mode have nearly the same frequency.

3. MEASURED MODES OF STRUCTURES

3.1 CERN/DESY structure.

The 4-cell CERN/DESY structure is being used at a number of laboratories in different parts of the world. A 350 MHz version of the structure is being used at CERN, a 500 MHz version is being used at DESY, Frascati, and JAERI and a 1300 MHz version is being used at Stanford. The lowest frequency longitudinal and transverse modes of the 1300 MHz version of this important structure are shown in Fig. 3.

In the CERN/DESY structure there are four longitudinal modes resonant at frequencies below 1.1 kHz. As can be seen in the figure, longitudinal motion is made possible by flexing of the cell walls near the irises. The observed spectrum of modes can be understood in terms of a spring and mass model of the structure where the cell equators and beam tubes are modeled with masses and the irises are modeled with springs. This model generates a set of 6 longitudinal modes, which, in the real structure, will be followed by further sets of modes at higher frequency. Such additional modes are a consequence of more rigid parts of the structure becoming flexible as the frequency is increased. It should be noted that the beam tube is rigid at low frequencies but its necking transition becomes flexible above 800 Hz, as seen in the n=4 longitudinal mode profile.

MECHANICAL MODES OF 4-CELL CERN/DESY STRUCTURE

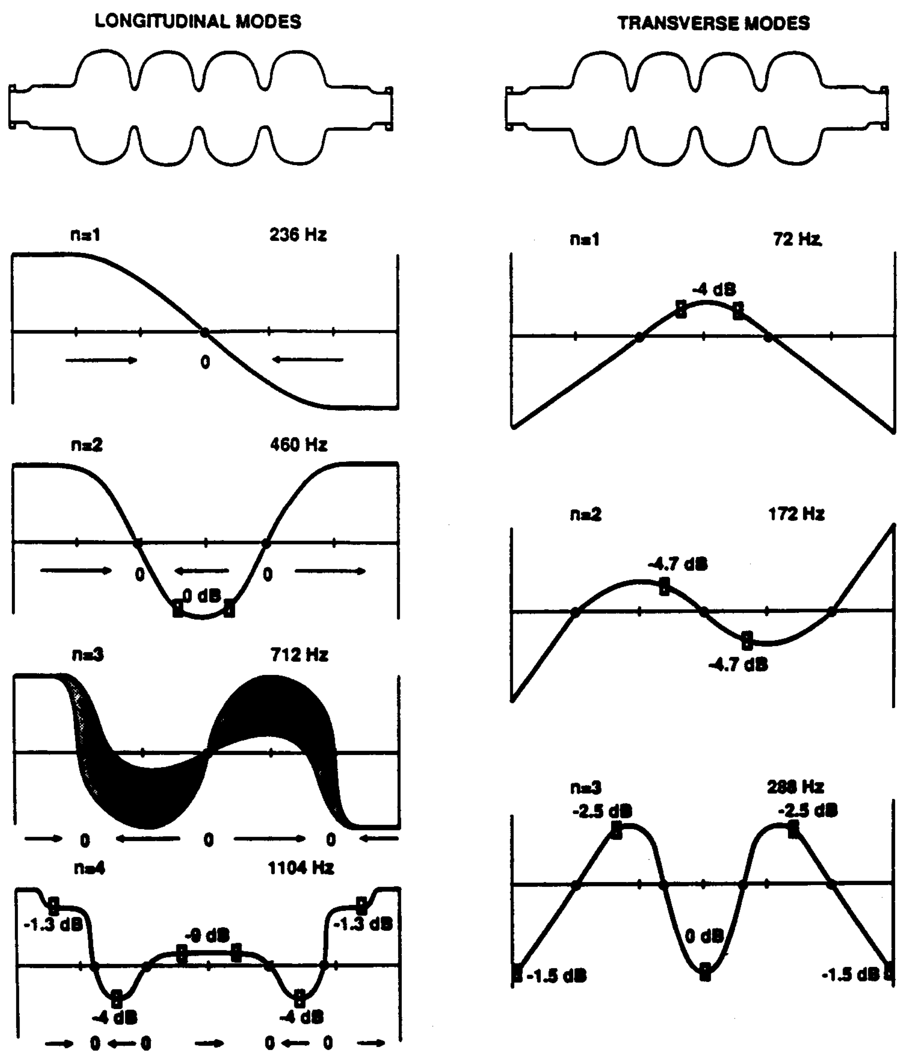

Fig 3. Lowest longitudinal and transverse mechanical modes of the 4-cell CERN/DESY structure. The third longitudinal mode was mixed with a transverse mode, and thus the mode profile was not precisely determined.

The transverse mode spectrum consists of only 3 modes, the lowest being at 72 Hz. Flexing of the structure at the irises is responsible for the motion in these modes. The fact that a fourth mode does not occur in this pattern, indicates that a mode with five nodes cannot be generated simply by bending at the irises. The next transverse mode is believed to be near 712 Hz and must be part of a new set of modes which requires greater flexibility than simple iris bending. Torsional modes were found at 652 Hz and 1220 Hz.

The mode measurements indicate that the irises are, as expected, the weak points of the structure and are responsible for generating the lowest longitudinal and transverse modes.

3.2 Stanford structure.

The original 7-cell Stanford structure was designed with six longitudinal rods welded to the cell equators. The rods provide extra rigidity in both the longitudinal and transverse directions. Since no microphonics problems have been observed in the operation of this structure[6], we analyzed its mechanical vibrational spectrum to characterize what has proved to be a successful stiffening system. The measured modes are shown in Fig. 4.

MECHANICAL MODES OF 7-CELL STANFORD STRUCTURE (WITH LONGITUDINAL RODS)

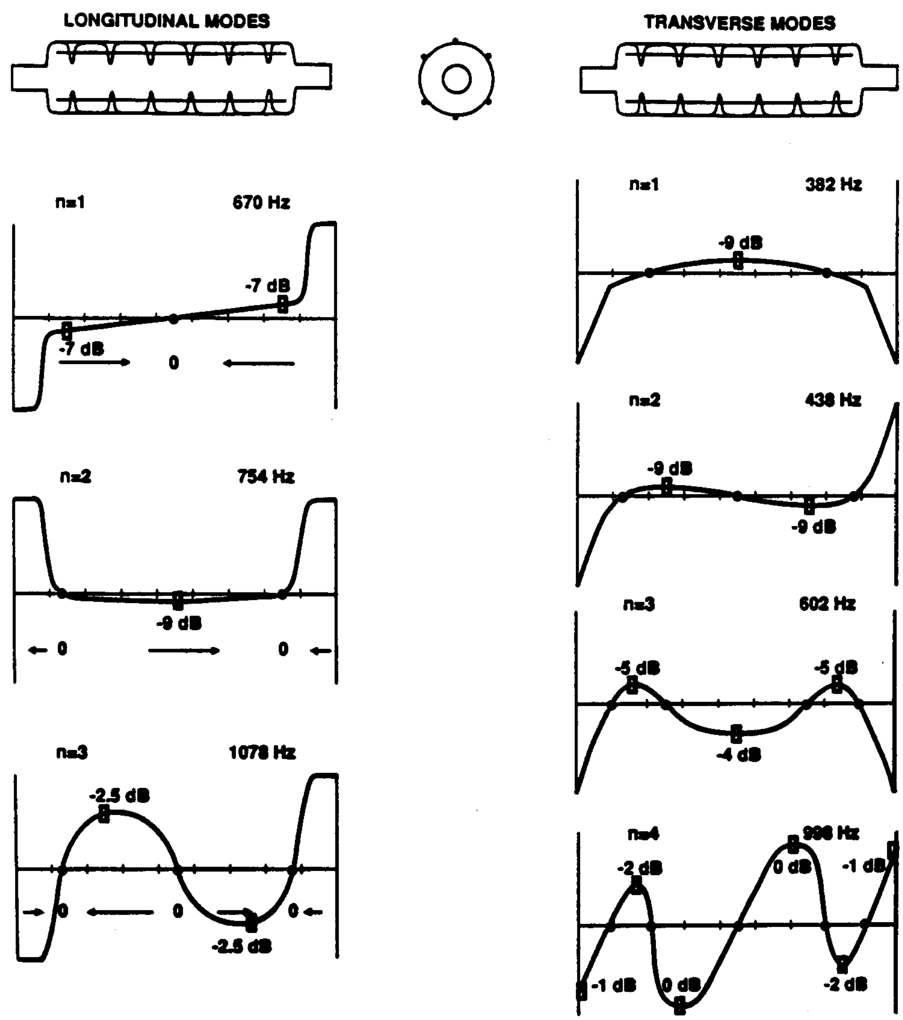

Fig 4. Lowest longitudinal and transverse modes of 7-cell Stanford structure. As indicated, there are longitudinal rods welded to this structure.

The Stanford structure has only three longitudinal modes below 1.1 kHz, the lowest being at 670 Hz. Of these three modes, the first two are paired together as beam tube oscillations, generated by the flexibility in the cell walls joined to the beam tubes. The effect of the stiffening rods can be seen in the profile of these modes; the cells oscillate very little in comparison to the beam tubes. The next longitudinal mode at 1078 Hz belongs to a new set of modes in which the stiffened part of the structure is now becoming flexible. It can be seen that, although the amplitude of oscillation of the beam tubes is still larger, the rigid part of the structure is flexing considerably.

The transverse mode spectrum can be divided up in the same way as the longitudinal spectrum. Bending of the cell walls at the beam tube connections is responsible for generating the lowest two modes in this spectrum, the lowest being at 382 Hz. Once again, the profiles show little motion in the stiffened part of the structure. The third mode at 602 Hz begins to show substantial bending of the stiffened part of the structure, while in the fourth mode the biggest amplitude of motion actually occurs in the section stiffened by the rods. In fact, if one ignores the beam tubes, the third and fourth modes correspond to the n=1 and n=2 modes of the stiffened part of the structure (compare with the transverse n=1 and n=2 modes in Fig. 3).

Torsional modes were also measured for this structure at 450 Hz and 914 Hz. The longitudinal rods did not appear to increase the rigidity of the structure for this type of motion.

The measurements indicate that the welded rods raised the frequencies of the lowest longitudinal and transverse modes by a significant factor. Without rods the lowest longitudinal and transverse frequencies for the Stanford structure would be approximately 150 Hz and 50 Hz respectively. With the rods, the frequency of the lowest longitudinal mode was increased by a factor of 4 and the lowest transverse mode by a factor of 8. It is clear that if stiffening rods had been extended to the beam tube flanges, the frequencies would have increased still further.

3.3 CERN/DESY structure with longitudinal support rods.

Mechanical mode measurements have also been made on a 4-cell CERN/DESY structure with longitudinal rods. In this structure, three 1/2 inch threaded rods equally spaced around the equator of the structure provide stiffening. The rods pass through anchors that are welded on each cell.

The mode measurements are shown in Fig. 5. Both longitudinal and transverse spectra are raised substantially in frequency by the rods and are now comparable to the spectra of the Stanford structure. Once again, it can be seen that the lowest modes of

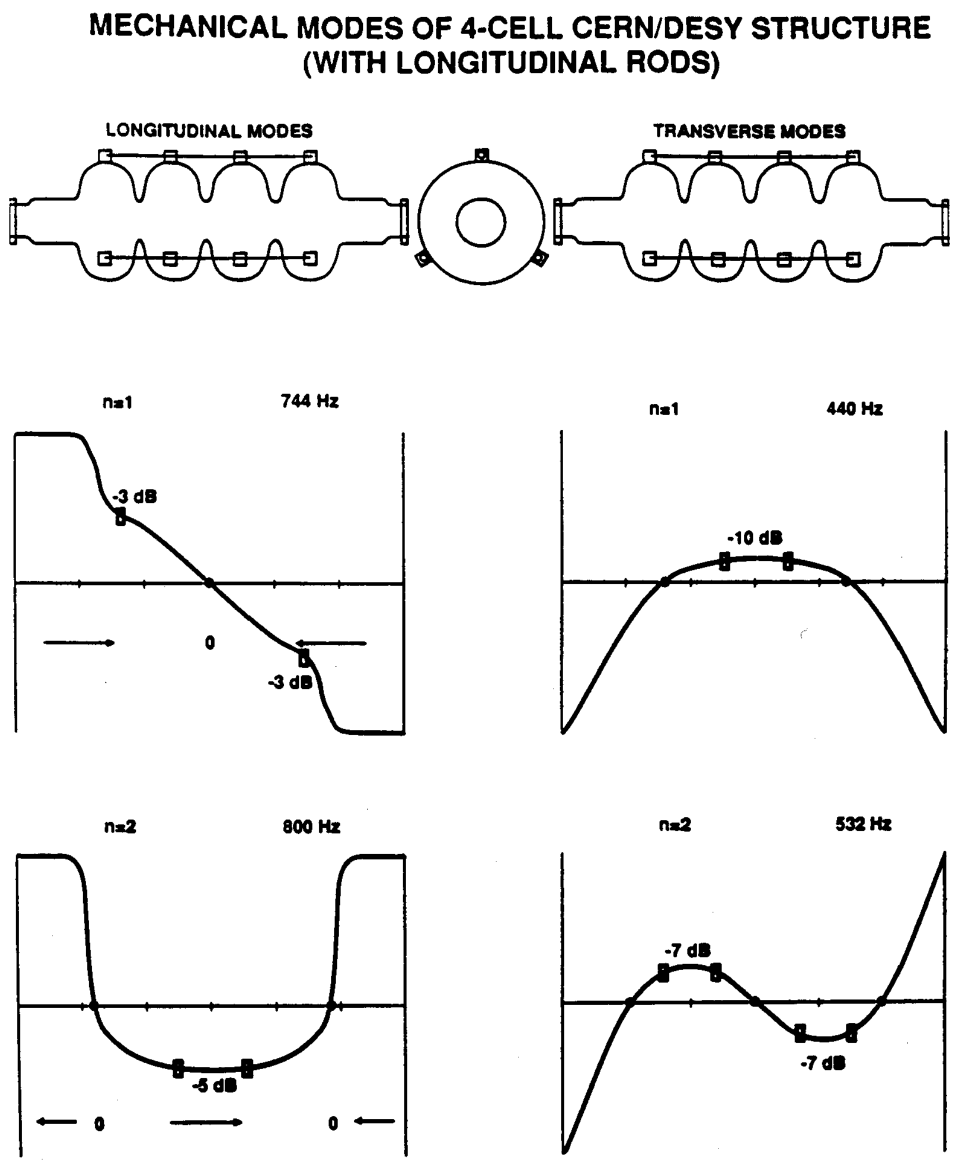

Fig 5. Lowest longitudinal and transverse modes of the 4-cell CERN/DESY structure with three longitudinal rods.

each type are caused by flexing of the cell walls connected to the beam tubes. Although the mode frequencies are comparable, it should be noted that amplitude of motion of the interior cells is somewhat greater than in the original Stanford structure, presumably because there are only three longitudinal rods. Torsional modes were measured at 584 Hz and 1104 Hz. Overall, the three longitudinal rods have proved very effective, although it may still be desirable to extend longitudinal support to the beam tube flanges.

4. CONSTRAINTS, ISOLATION AND DAMPING

4.1 End Constraints.

The vibrational mode spectrum of a multi-cell linac structure will be influenced by the support system and tuning system employed. In an idealized sense, these systems establish boundary conditions for the vibrational mode problem. General features of this problem can be ascertained by considering the vibrational mode spectrum of a hollow cylinder for different clamping arrangements. The equations governing these spectra, the profile of the lowest frequency mode, and the relative frequencies of the lowest modes are given in Table 1.

LONGITUDINAL MODES

END CONSTRAINTS	PROFILE OF LOWEST MODE	$f_n = a_n\sqrt{\frac{E}{\rho}}\,\frac{1}{l}$	
FREE - FREE		$a_n = \frac{n}{2}$	n = 1,2,3...
CLAMPED - CLAMPED		$a_n = \frac{n}{2}$	n = 1,2,3...
CLAMPED - HINGED		$a_n = \frac{n}{2}$	n = 1,2,3...
CLAMPED - FREE		$a_n = \frac{1}{4}(2n-1)$	n = 1,2,3...

TRANSVERSE MODES

END CONSTRAINTS	PROFILE OF LOWEST MODE	$f_n = a_n\sqrt{\frac{E}{\rho}}\,\frac{\sqrt{d^2+D^2}}{l}$	
FREE - FREE		$a_1 = 22.0$ $a_3 = 121$	$a_2 = 61.7$ $a_4 = 200$
CLAMPED - CLAMPED		$a_1 = 22.0$ $a_3 = 121$	$a_2 = 61.7$ $a_4 = 200$
CLAMPED - HINGED		$a_1 = 15.4$ $a_3 = 104$	$a_2 = 50.0$ $a_4 = 178$
CLAMPED - FREE		$a_1 = 3.52$ $a_3 = 61.7$	$a_2 = 22.0$ $a_4 = 121$

l = LENGTH, d = INNER DIA., D = OUTER DIA., E = YOUNG'S MODULUS, ρ = DENSITY

Table 1. Longitudinal and transverse modes of a hollow cylinder with various end constraints.

For these idealized end constraints, it can be seen that the mode spectrum is the same for the FREE - FREE arrangement and the CLAMPED - CLAMPED arrangement. It should be noted that although the mode spectra are the same, the effects on accelerator operation is not. For instance, the anti-symmetric longitudinal modes in the FREE - FREE arrangement produce a modulation of structure length and therefore a modulation of structure frequency. There is clearly no change in structure length for any mode in an ideal CLAMPED - CLAMPED arrangement.

The mode spectra for the CLAMPED - FREE and the CLAMPED - HINGED arrangements are substantially different from the spectra discussed above, particularly for the transverse modes. The frequency of the lowest transverse mode for the CLAMPED - FREE arrangement is reduced by a factor of 6.25 from the FREE - FREE arrangement, while for the CLAMPED - HINGED arrangement it is reduced by a factor of 1.4. In practice, lower resonant frequencies make the structure more susceptible to microphonics and thus the CLAMPED - FREE and the CLAMPED - HINGED arrangements are undesirable.

It is difficult in a real system to achieve any of the idealized end constraints described above. Any real support system or tuning system will have its own spectrum of mechanical frequencies and may oscillate together with the structure it was intended to constrain.

A particularly dramatic example of this kind of combined oscillation can be seen in Fig. 6. Note that the mode profile resembles a FREE - FREE mode as opposed to a CLAMPED - CLAMPED mode.

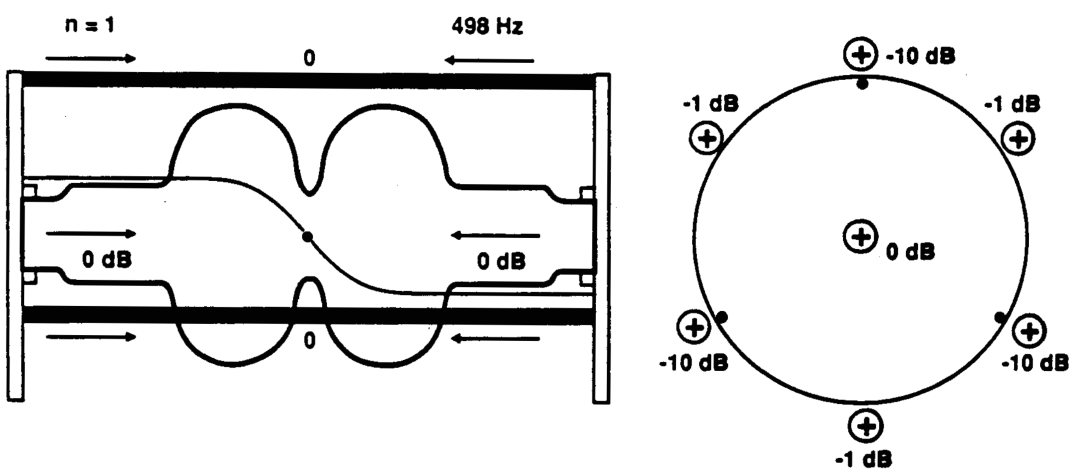

Fig 6. Lowest longitudinal mode of a 2-cell structure clamped by an inadequate support structure. Substantial movement of the ends of the structure shows that clamping of the ends has not been achieved. This is a result of a near overlap of the 434 Hz Free - Free n=1 longitudinal mode of the 2 cell structure and similar modes of the support system at approximately 482 Hz and 600 Hz.

4.2 Isolation and Damping.

Although it is clearly an advantage to increase the frequencies of the lowest vibrational modes, one can also attack the microphonics problem by isolation of the linac structure from acoustic noise sources and by damping. As pointed out earlier, the original superconducting linac structure at Stanford was cradled in the helium dewar by a low frequency support system that provided both isolation and damping. In addition, some effort was made to reduce direct acoustic noise transmission through the RF input. Evaluation of the isolation and damping provided by the overall cryogenic system design is important but is beyond the scope of this paper.

5. CONCLUSIONS

The issues discussed in this paper are particularly important for electron linac applications where pointing stability, position stability, and electron beam energy stability are crucial. Several Free Electron Laser applications require pointing and position stability of the electron beam at the 0.1 mr and 0.1 mm level, and require electron beam energy stability at the 5×10^{-5} level. Only the superconducting linac at Stanford has demonstrated operation at a level approaching this.

Based on the studies in this paper we would conclude that 1) a stiffening system of three longitudinal rods anchored at each cell is effective in raising the vibrational frequencies of the structure, 2) extension of longitudinal support to the beam tube flanges is desirable, and 3) great care must be exercised in the design of the structure support system and tuning system. Although issues of isolation and damping are beyond the immediate scope of this paper, it is clear that these must also be incorporated in the design of a highly stable electron linac.

6. ACKNOWLEDGMENTS

This work was supported by the Office of Naval Research under Contract Number ONR N00014-91-C-0170.

7. REFERENCES

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