Vibration Analysis of the Photon Shutter Designed for the Advanced Photon Source

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DRAFT

Abstract

The photon shutter is a critical component of the beamline front end for the 7 GeV Advanced Photon Source (APS) project, now under construction at Argonne National Laboratory (ANL). The shutter is designed to close in tens of milliseconds to absorb up to 10 kW heat load (with high heat flux). Our shutter design uses innovative enhanced heat transfer tubes to withstand the high heat load. Although designed to be light weight and compact, the very fast movement of the shutter gives rise to concern regarding vibration and dynamic sensitivity. To guarantee long-term functionality and reliability of the shutter, the dynamic behavior should be fully studied. In this paper, the natural frequency and transient dynamic analysis for the shutter during operation are presented. Through analysis of the vibration characteristics, as well as stress and deformation, several options in design were developed and compared, including selection of materials for the shutter and structural details.

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Introduction

The photon shutter is a critical component of the insertion device (ID) beamline front end. This component is designed to close in tens of milliseconds. The design uses innovative enhanced heat transfer tubes to withstand up to 10 kW heat load coming off the 5 m long future Undulator A ID of the Advanced Photon Source project at Argonne National Laboratory. Currently, the shutter is designed to handle 5.2 kW total beam power coming off a 2.5 m long Undulator A. Although designed to be light weight and compact, the very fast movement of the shutter gives rise to concern regarding vibration when the shutter is closed. To guarantee long-term functionality and reliability of the shutter, the dynamic characteristics should be fully analyzed. In this paper, the modal frequency and transient dynamic analyses for the shutter are presented. Through analysis of the vibration characteristics, as well as stress and deformation, several options in design were developed and compared, including selection of materials for the shutter and structural details.

Figure 1 shows the side view of the shutter, which is hinge fixed at the upper left side and connected to the actuator at 100 mm inside the right side. This point can move down to close the beamline and up to open the beamline. The shutter cuts the beam with a 1 degree angle to increase the area that intercepts the beam. The size of the shutter coil is decided mainly by the size of the flange. The flange is designed in such a way that the shutter assembly assembly can be removed in tact for maintenance. After the comparison of several structural designs, the current design was adopted which varies in thickness along the direction of the coil to get maximum stiffness and minimum total weight. Figure 2 shows the cross section of the shutter, which is composed of a continuous heat transfer coil which is clamped on the edges by two stainless steel stiffeners. Between the upper and lower heat transfer tubes of the shutter coil, there is an aluminum alloy stiffener which further increases the stiffness of the coil as well as the stiffness of the cross section. The coil tube is made of special copper and filled with copper foam in the heated zone to enhance the corrective heat transfer coefficient significantly.

The fast shutter actuation to close fast is the driving force for vibrations. To fully understand the dynamic characteristic of the shutter, natural frequency analysis was performed from which the frequency and mode shapes of the different mode of vibration can be known before dynamic transient analysis. The dynamic transient analysis, in turn, will decide the structural response during the closing of the shutter. The deformation and stress history of the shutter will be decided thereafter. The deformation and stress are very important for a successful design. The shutter is designed for at least 10 thousand life cycles and the deformation must be controlled to a minimum. The shutter tube is made of Glid-cop or oxygen free (OFHC) copper. One should be careful not to allow any portion of the shutter tube assembly to exceed the material yield point under cycle fatigue.

A commercial finite element code "ANSYS" is used for the modal frequency and dynamic transient analyses. In this paper we will first present the finite element modal of the shutter and the results from modal frequency analysis and dynamic transient analysis. Then we discuss the results and different design options and possible improvements to the current design.

Modal Frequency Analysis

With a design, the first concern is what the natural frequency will be and what the deformed structure looks like. To get the natural frequency and vibration mode, modal frequency analysis was first performed using the ANSYS code. Figure 3 is the finite element modal of the shutter, in which 5193 ANSYS STIF45 isoparametric solid elements and STIF63 shell elements were used to model the whole structure with a total of 8720 nodes. The mass of the shutter is 25.4 pounds The first six modes of the structure were analyzed with the results shown in Figs. 4 to 9. For each mode, the mode shape and corresponding frequency are plotted in the figures. The lowest frequency is 13.7 Hz and the corresponding first mode is dominant during the vibration (i.e. the structural response frequency is mainly decided by this frequency).

Dynamic Transient Analysis

For dynamic transient analysis, the assumption was made that the actuator follows the velocity profile shown in Fig. 10. The profile is idealized by assuming that the actuator will stop and stay still once the shutter is put in the position. The actual profile would exhibit damped vibrations of the actuator after the shutter is closed. The idealized profile will be more conservative because the acceleration and force will be smaller than what we used.

The maximum deformation and stress during the vibration are the main concerns. Two cases were analyzed: 10 ms and 100 ms actuation times. For the 10 ms case, the results show that the deformation was about 1 in. at the middle of the shutter. The acceleration at the connecting point with the actuator was 160 g. Such deformations and accelerations cannot be tolerated and will definitely cause yielding of the material. Due to the structural limits on the coil height of the cross section, 10 ms shutter with the present design cannot be achieved. For the 100 ms case, the g-load is about 1 g. The results from the 100 ms are shown in Figs. 11 to 15. Figure 11 is the displacement time history at different locations on the shutter which point 540 and point 3676 are at the middle of the copper tube and the stainless steel from the center of the shutter; point 527 and point 3663 are at 1/3 of the shutter length, corresponding respectively to the middle of the copper tube cross section and the bottom of the SS side plate. Point 8117 corresponds to the actuator. Figure 14 shows the velocities and accelerations respectively, at those points.

From Fig. 11, it is seen that the maximum displacement during the vibration will occur at 147 ms. In Figs. 15 to 16, the Mises stress of the top and bottom copper plate and the stainless steel are shown at the time of maximum deformation. The maximum Mises stress is 30 ksi for copper and 45 ksi for stainless steel. Stresses in both the copper and stainless steel materials are well below the the yield point. The maximum deformation occurs at 1/3 the length of the shutter and is about 2 mm as seen in Fig. 12. This is considered to satisfy the design criteria. By comparing the maximum stress and S-N curve of the copper, one can estimate that the fatigue life of 10^5 well satisfies the design life cycles.

With this transient dynamic analysis, it is shown that the current shutter design for the 2.5 m long Undulator A front end satisfies long-term functionality and reliability.

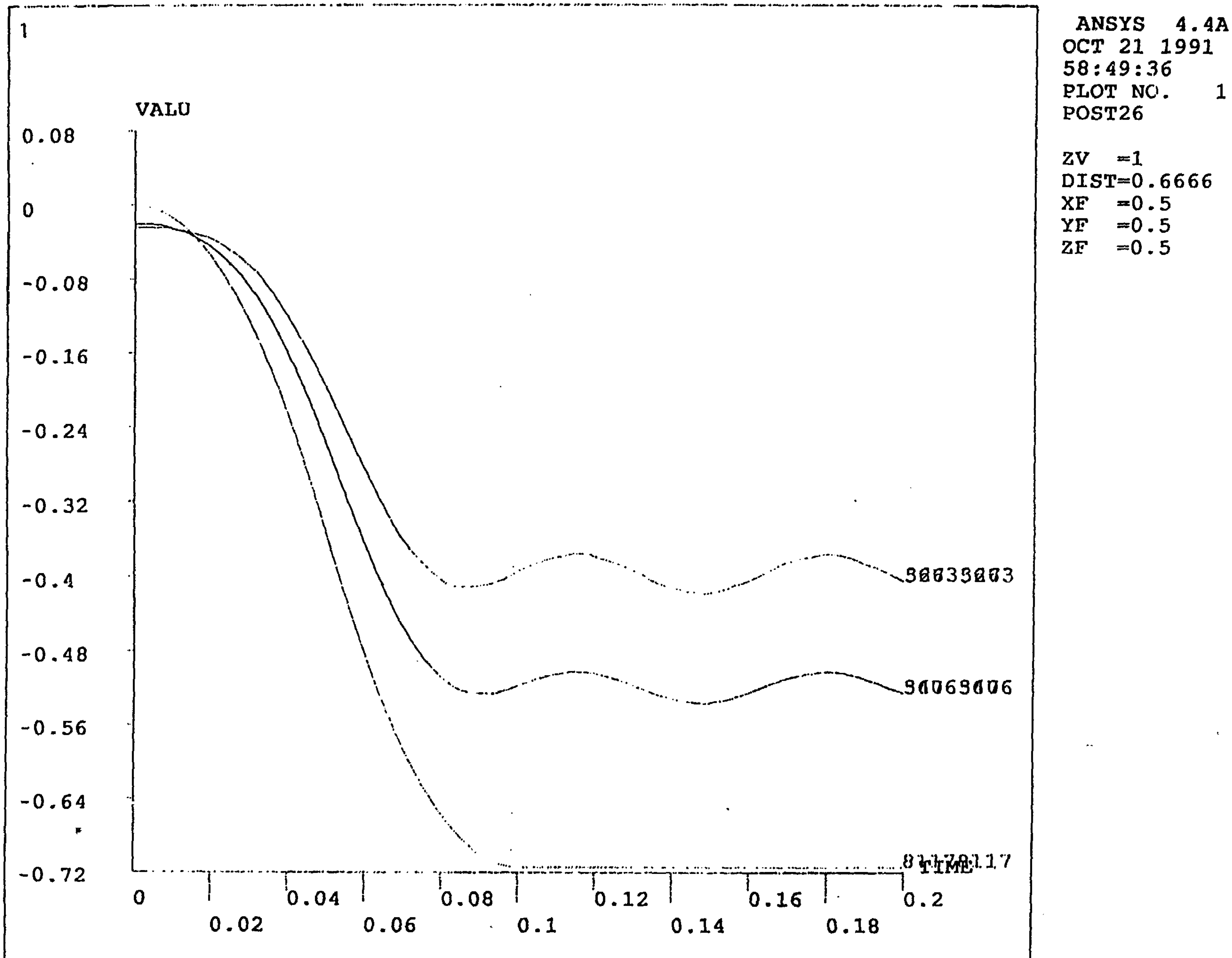
Conclusions

This study is a comparative vibration/stress analysis of a very fast (100 ms) photon shutter design. For the 10 ms case, it is impossible for the present shutter design to separate without excessive deformation and stresses and is likely fail. While for the 100 ms case, analysis shows that the structural design can withstand the vibrations with acceptable deformation and stress. It is also possible to design the shutter to close in 50 ms. Since there is no big difference between a 100 ms design and a 50 ms design, we consider the 100 ms shutter analysis here.

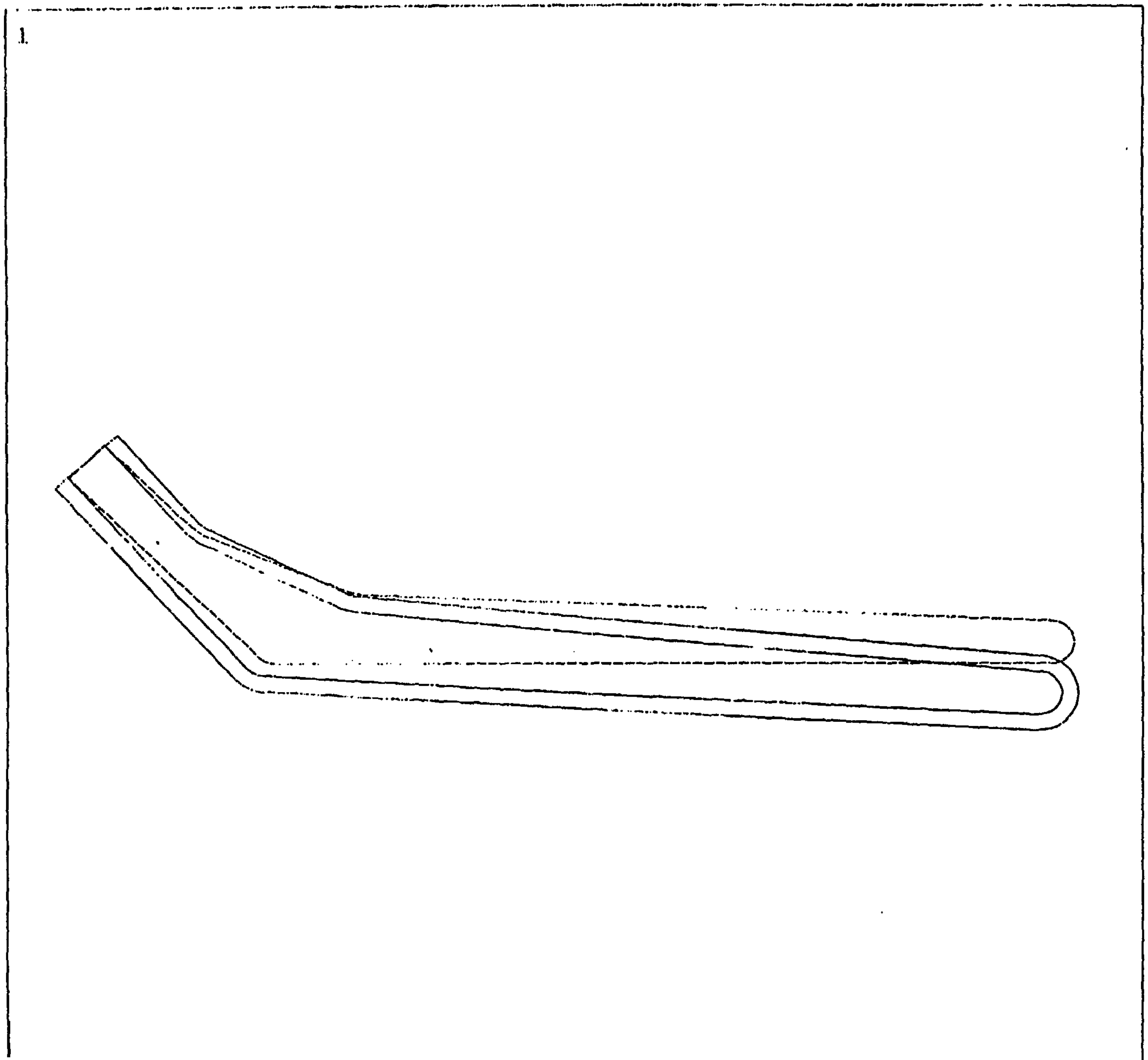
Several different structural designs were investigated from both the modal frequency and dynamic transient analyses basis. It is shown that the current shutter design with a variable width of the shutter coil will meet the vibration concerns in operations. The maximum deformation is within 2 mm at 1/3 the length of the shutter and the stresses in the tube material and the stiffening material are all well below the material yield values.

References

[1]. Gabriel J. DeSalvo and Robert W. Gorman, ANSYS Engineering Analysis System User's Manual, May,1989.



Vibration analysis of shutter Model V



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OCT 21 1991
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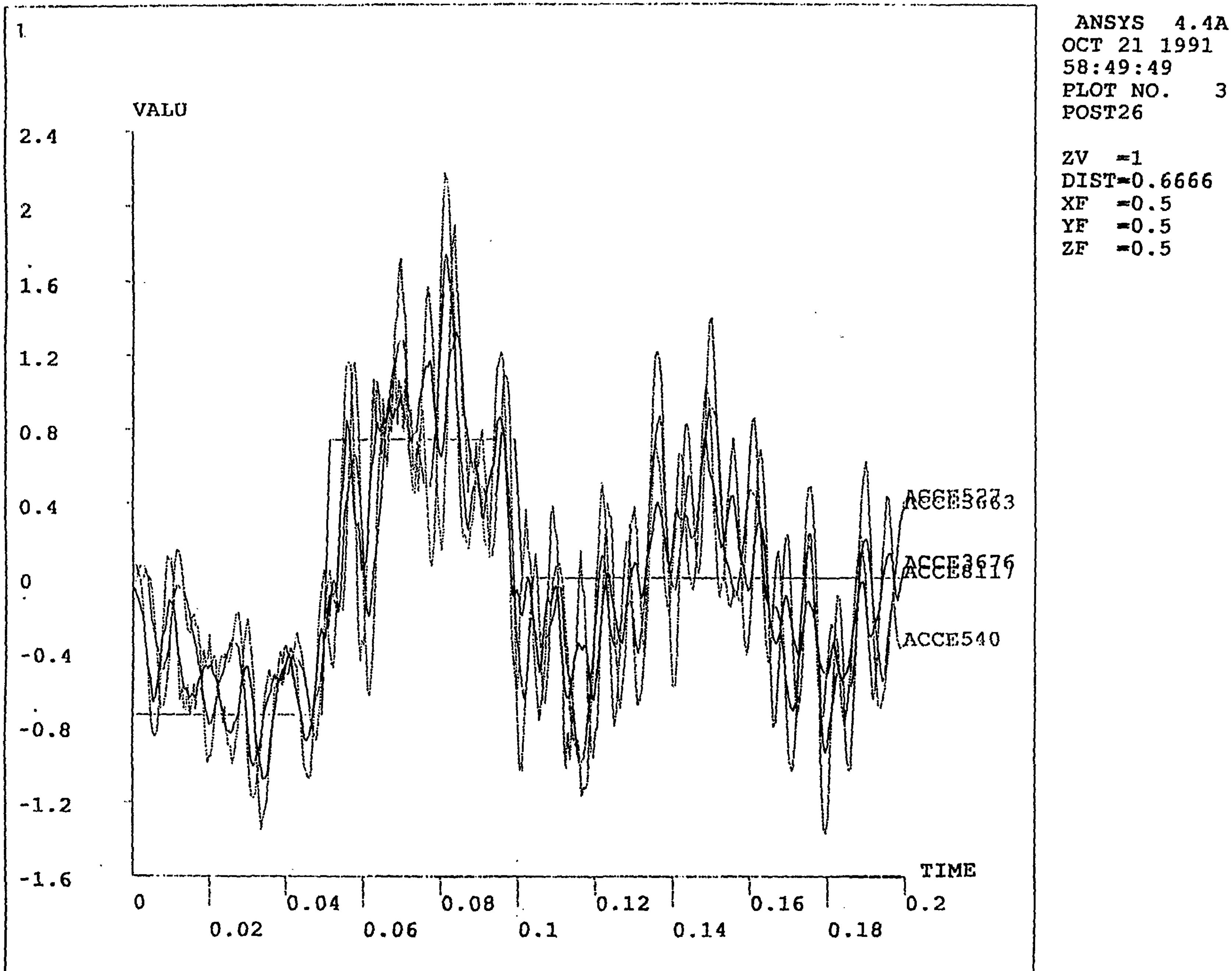
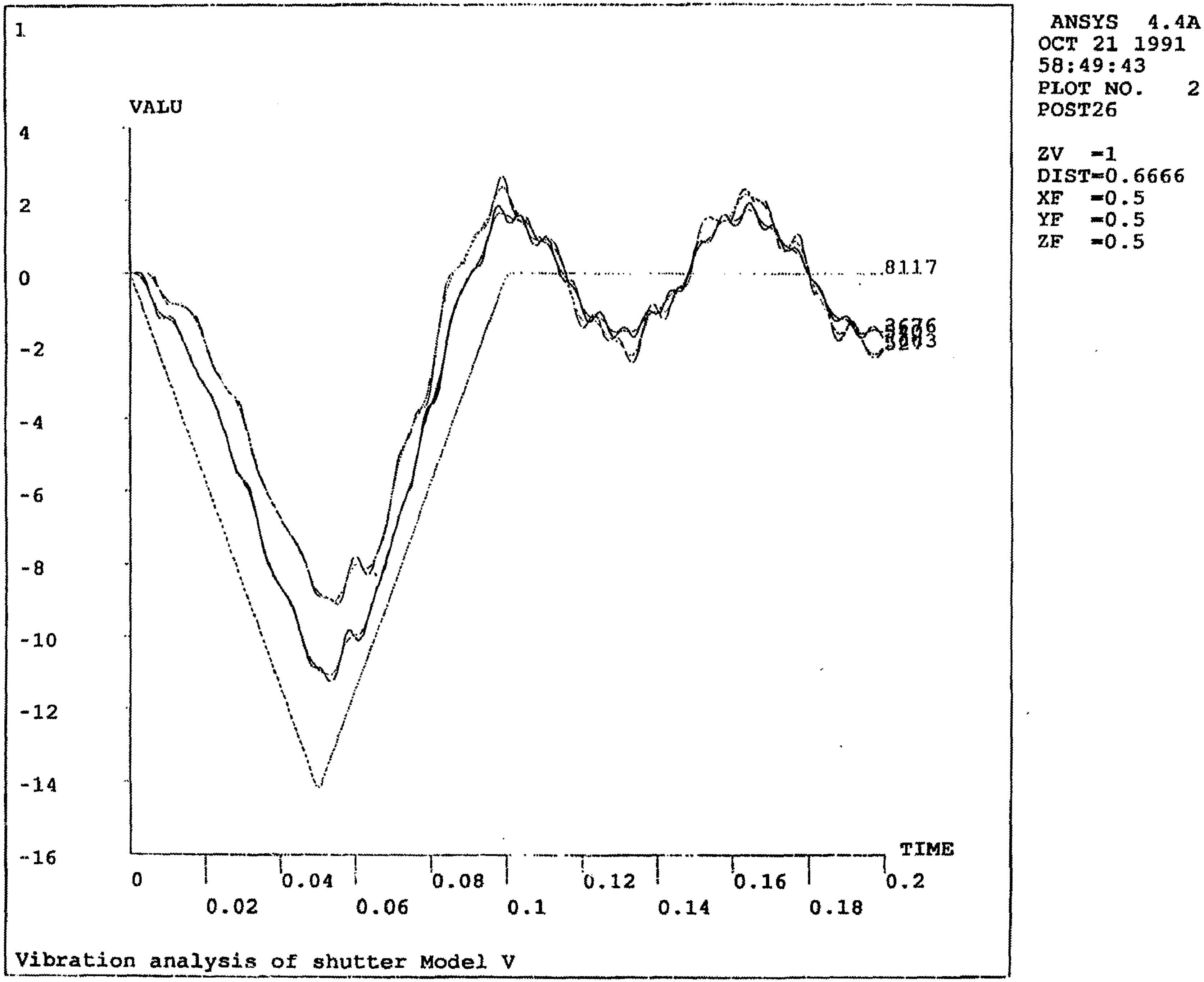


Vibration analysis of shutter Model V



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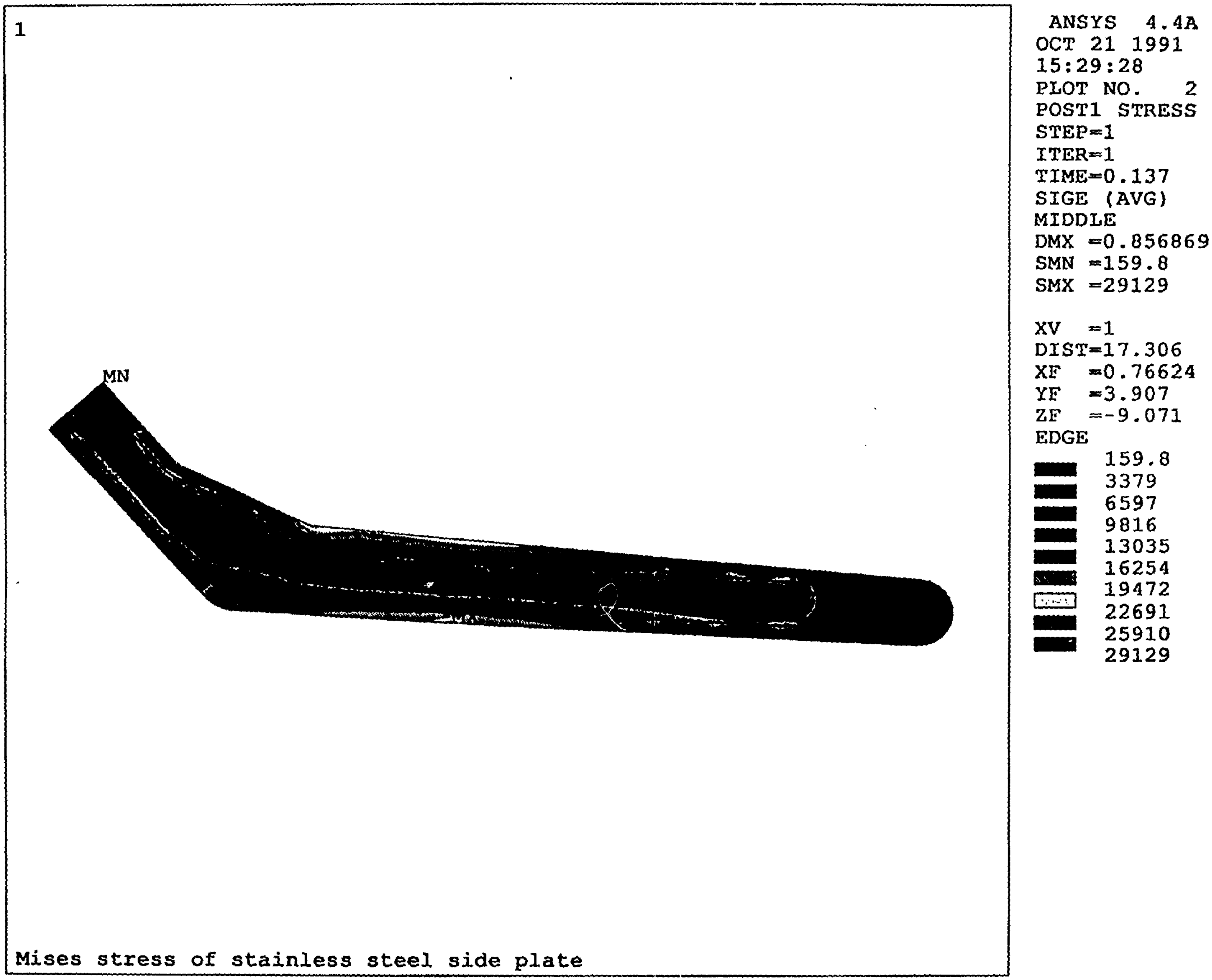
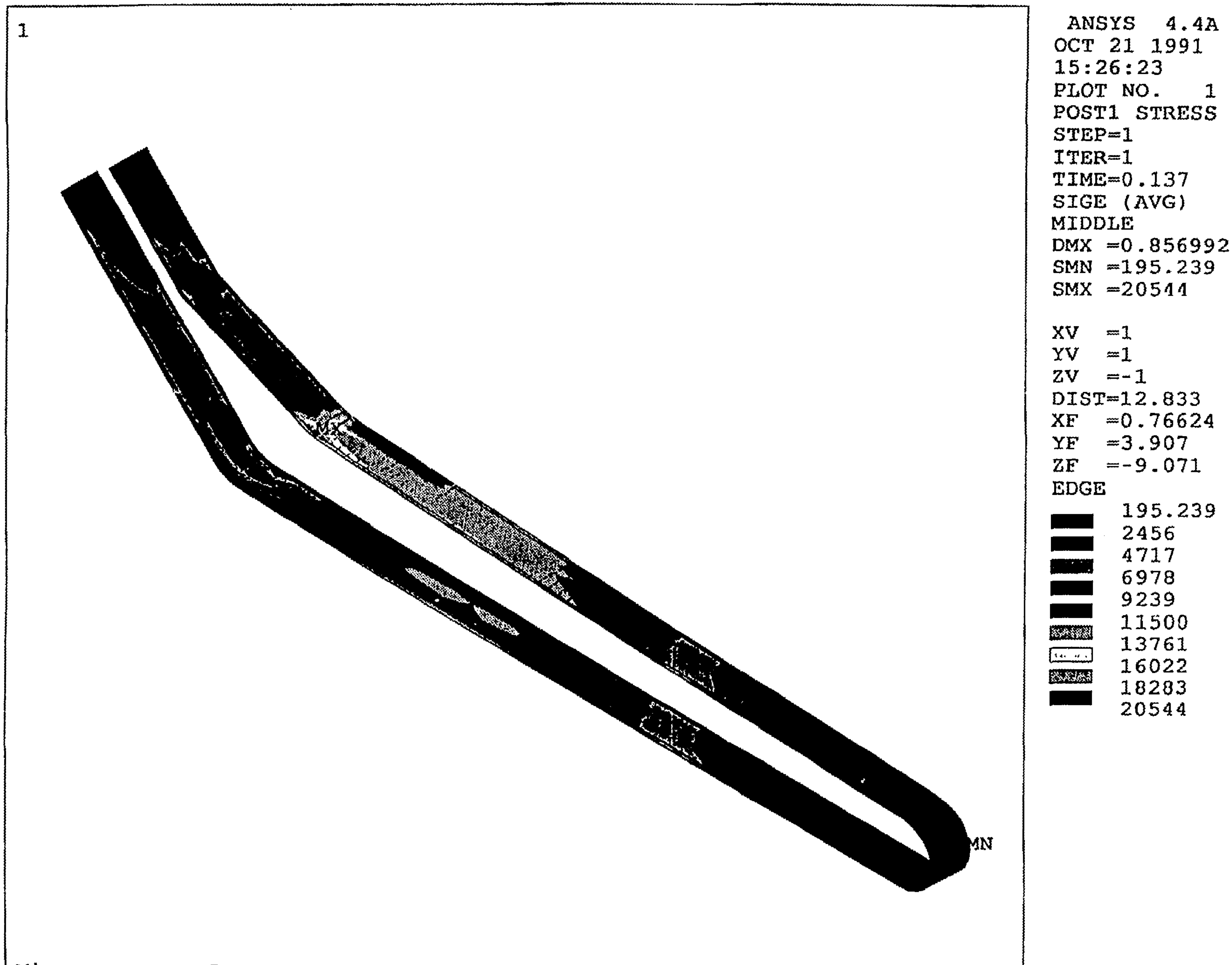
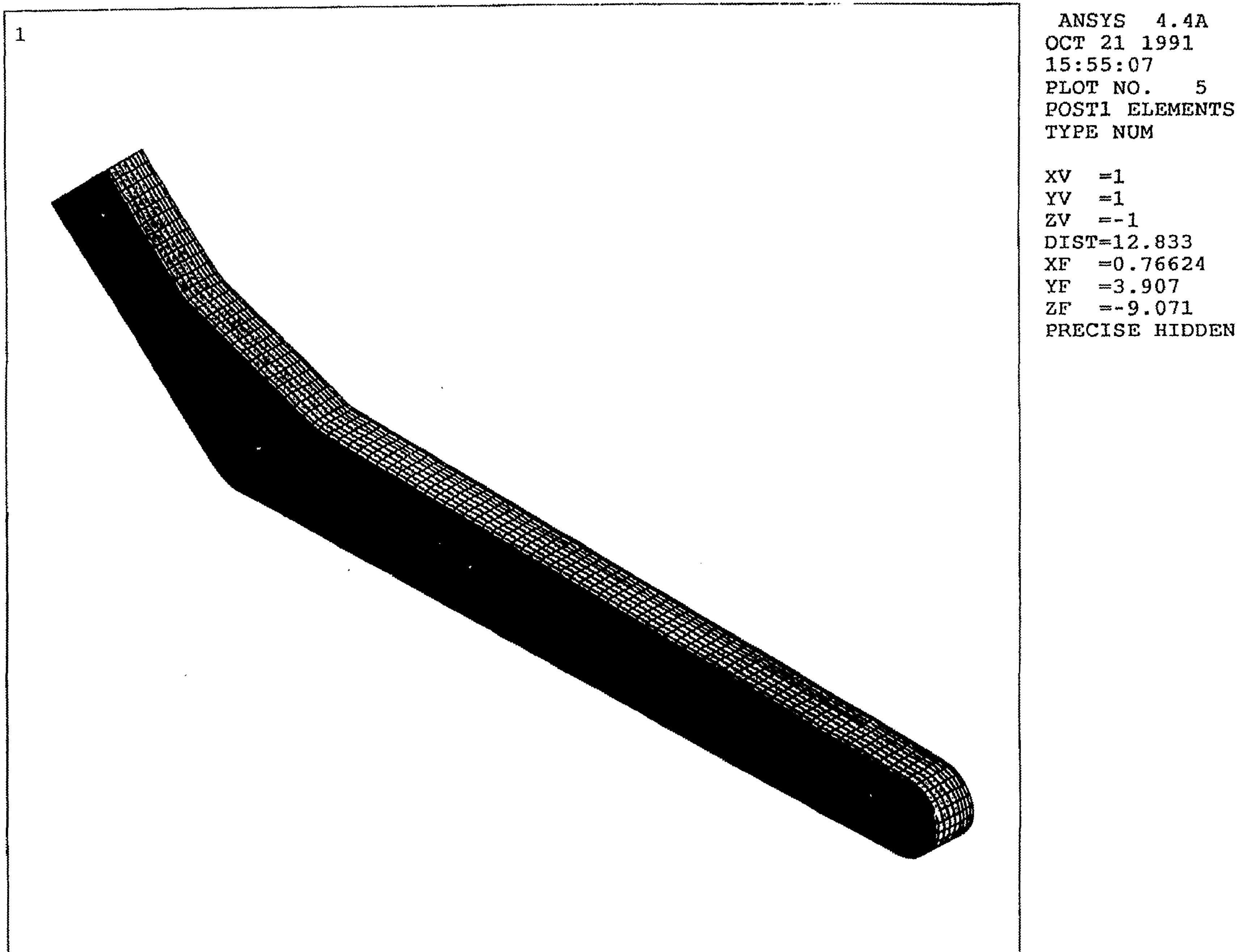
Vibration analysis of shutter Model V



Mises stress of stainless steel side plate



Mises stress of upper and bottom faces of copper tube



Elements plot of the shutter model