IDENTIFICATION OF ROOT CAUSE AND ABATEMENT OF VIBRATION OF MONOCHROMATOR

by

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DISCLAIMER

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Introduction

Silicon crystal mirrors are used to reflect high-intensity X-ray beams. A large amount of heat is generated in each mirror. To minimize the effect of thermal expansion on the crystal mirrors, heat is removed by pumping liquid gallium (with a boiling point of 29.8°C) through passages in the crystal mirrors.

During system operation, mirror motion should be kept to an acceptable level to avoid performance degradation. There are many potential sources of excitation to the crystal assembly; one such source is the flowing gallium. Two series of tests were performed earlier for a near-prototypical gallium cooling system (1-2). This paper describes a series of tests to measure the general vibration response characteristics of critical components in the monochromator system that contains the mirrors.

The main objective of this work is to identify the root cause of vibration and to recommend general guidelines for abatement of vibration. This is achieved by performing many tests to understand the response characteristics under various conditions, by analysis of the response data, and by use of some theoretical considerations.

Technical Approach

A general view of the monochromator system is shown in Fig. 1. The critical component, the crystal mirror assembly and schematic diagrams of the cooling flow loops are given in Fig. 2. The normal operating flow loop is Configuration B. shown in Fig. 2. However, most of the tests were conducted under Configuration A because that was the original arrangement when the test facility was made available for this program. For the later experiments, the inlet and outlets were switched to create Configuration B. In this paper, all tests not otherwise noted were conducted under Configuration A.

Motions that are important to identification of the root cause of the vibration were measured at selected locations. Seven accelerometers were used in the tests. Different tests, each with a specific purpose, were performed in a laboratory:

Background Excitation: Without cooling flow and other external excitation, acceleration was measured at various locations.

Natural Frequencies: Important components were tested with a small external impact to excite the natural frequencies.

Pumping Excitation: With the pump running but no flow passing through the system, acceleration at different locations was measured.

Flow Excitation: Acceleration at various locations was measured as a function of flow rate, and effects of temperature and pressure were studied.

Modifications: With some minor modifications to the system, response at various locations was measured in an attempt to understand the effect of the modifications.

Survey Tests

Acceleration measured from seven accelerometers was recorded by an analyzer and then integrated twice to obtain displacements. The power spectra of both acceleration and displacement from the accelerometers were recorded for analysis. A key piece of information is RMS displacement at all locations. In all tests, the frequency range considered is 4 to 200 Hz; for frequencies of <4 Hz, the displacement-time histories are contaminated with integrator noise.

Background Excitation

Floor. Seven accelerometers were placed on the floor along a line about 30.48 cm west of the supporting table. With no excitation, displacement from the seven accelerometers ranged from 0.026 to 0.053 μm, with an average of 0.04 μm. Thus, the background excitation from the ambient floor motion is low and is typical of ambient experimental hall floor motion measured previously (3). Exciting the floor by jumping only a few feet away from the accelerometers increased displacement more than 10 times, ranging from ≈0.15 μm to 0.75 μm.

Floor and Table. One of the accelerometers was removed and placed on the top of the table to measure the motion of the table in the vertical direction. Based on an average of the six accelerometers, the RMS floor displacement is 0.036 μm, which is close to the previous measurement of 0.04 μm. The RMS displacement of the table is 0.06 μm. The motion of the table is larger than that of the floor but remains relatively small.

Table and Crystal Mirror. An accelerometer was placed at each of three locations to measure the motion

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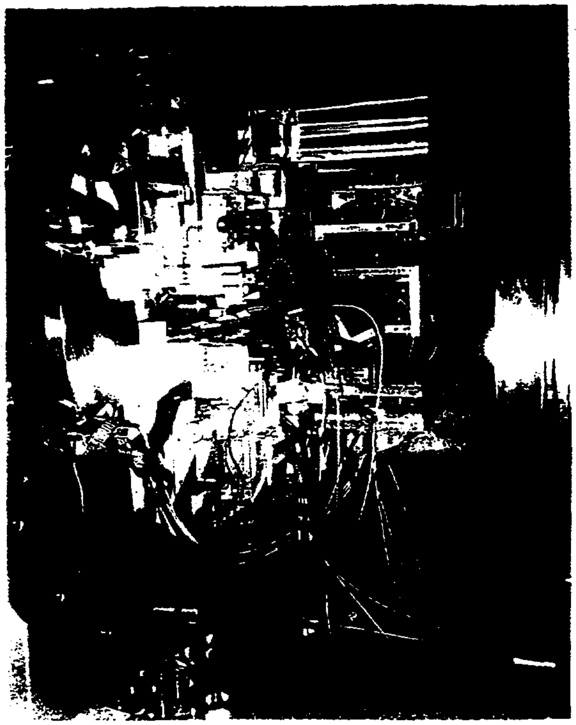


Fig. 1. General view of monochromator

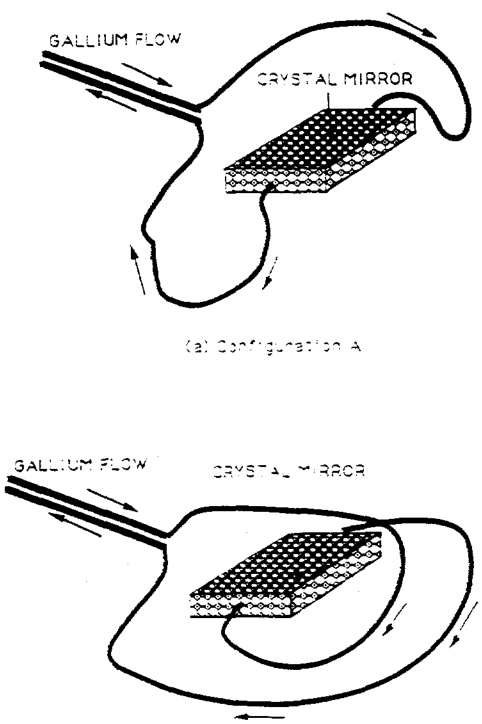


Fig. 2. Gallium loop configurations

of the table in three orthogonal directions. Accelerometers were also placed at each of four locations (C1, C2, C3, and C4) indicated in Fig. 3. Figures 3a and 3b are photographs taken from the east side and west side of the table, respectively. In later tests, the accelerometers were moved to locations B1, U1, and either P1 or P2. The accelerometers at C1, C2, C3, and C4 were intended to measure the motions of the crystal assembly:

C1: On top of the west side of the crystal mirror, to measure motion in the vertical direction.

C2: On top of the east side of the crystal mirror, to measure motion in the vertical direction.

C3: On the back of the crystal mirror, to measure motion in approximately a horizontal plane in the south and north directions.

C4: On the east end of the crystal mirror, to measure the axial motion of the crystal assembly along the east and west directions.

The displacements were recorded for several periods, 8 sec in each period. Values obtained from the seven locations vary from 0.030 to 0.070 μm. On the basis of these measurements, we conclude that excitation due to ambient background noise is relatively small.

Natural Frequencies of Table and Crystal Mirror

The natural frequencies of the crystal mirror and supporting table were measured, with the objective of understanding the dominant modes. The frequencies were identified from the power spectra of accelerations resulting from a series of small impacts. From the PSD curves, the dominant modes can be identified. Different impacts were used to excite different modes. The following natural frequencies were identified:

Table:	7 Hz	Up and down motion.
	35 Hz	North and south motion along the length of the table.
Crystal	82 Hz	Up and down motion.
Mirror:	122 Hz	East and west motion along the axis of the mirror.

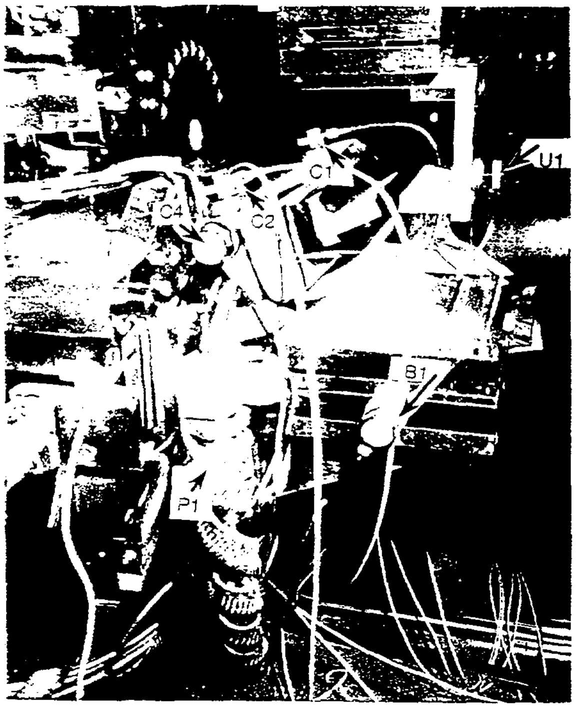
These are the dominant frequencies that can be identified from the impact tests. The natural frequencies in the other directions for both table and mirror were difficult to excite.

Pumping System Excitation

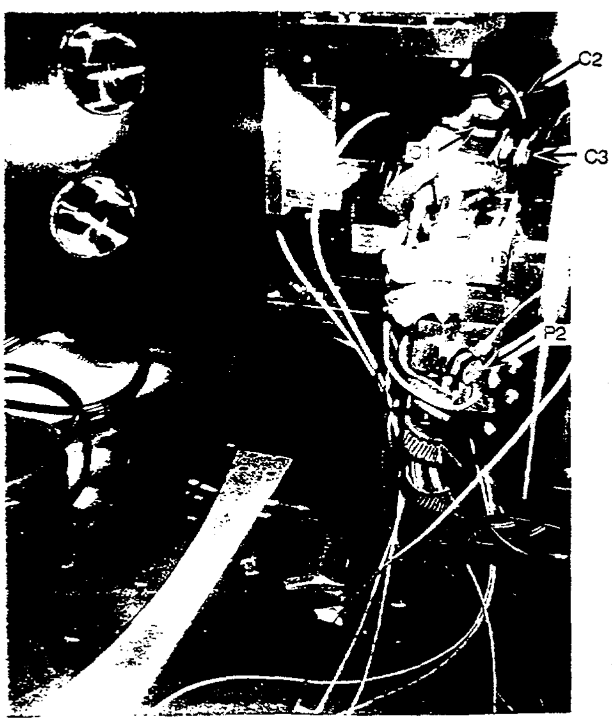
RMS displacements at the seven locations were measured while the pumping system was operating, but with no flow passing through the monochromator. Displacements vary from 0.073 to 0.123 μm. The pumping system excites measurably larger motions. Nevertheless, motions of the supporting table and crystal assembly due to pump excitations remain fairly small.

Table Vibration Due to Flow

Table response was measured as a function of flow velocity. Vibration of the table is essentially independent of flow rate. The excitation provided by the flow is ineffective in exciting the table vibration.



(a)



(b)

Fig. 3. Locations of accelerometers (a) facing west: C1, C2, C4, B1, U1, and P1; and (b) facing east: C1, C2, C3, and P2

Summary

On the basis of these scoping tests, it may be concluded that: (a) Motions of the crystal assembly due to ambient background noises are fairly small; (b)Vibrations of the crystal assembly due to operation of the gallium pumping system, with the flow bypassing the monochromator, are still fairly small; (c) Response of the supporting table to gallium flow is small and is almost independent of flow rate; and (d) The main excitation source of the crystal assembly is associated with gallium flow. The subsequent tests were directed to the gallium-flow-induced vibration of the crystal assembly.

Flow-Induced Vibration of Crystal Assembly

Tests were performed for both loop configurations A and B, and the accelerometers at these three locations measured the following motions:

U1: Attached to the support of the second mirror, to measure motion along the north and south directions.

B1: Attached to the base of the support of the crystal assembly, to measure motion in the east and west directions.

P1: Attached to the nut connecting the 90° steel angle and Teflon pipe, to measure motion in the horizontal plane approximately in the southeast direction.

Loop Configuration A

Because the gallium loop was initially set up in configuration A, extensive tests were conducted for that configuration. In particular, the following series of tests were performed:

A. Accelerations and displacements were measured by decreasing and increasing flow rate.

B. Accelerometers were exchanged at various locations, and tests were repeated.

C. Loop temperature was changed, and similar tests were run.

D. Support conditions of the Teflon pipes and crystal assembly were modified, and motion was measured again.

Test A.1: General Response. Motion was measured as a function of flow rate with increasing or decreasing flow rate. The RMS displacements are given in Fig. 4; note that Figs. 4a, 4b, and 4c are in linear scale, while Fig. 4d is in logarithmic scale. Once the flow rate reaches ≈1.6 gallons per minute (gpm), the RMS displacements at locations C1, C2, C3, and C4 increase dramatically. This can be seen more clearly in Fig. 4d; the slope of the curve to correlate the data from locations C1, C2, C3, and C4 will be much larger than 2. This will become more clear from the results of other tests. If the motion of a system with a fixed condition is induced by flow, the response is expected to be proportional to approximately the second power of the flow rate.

Test A.2: General Response. This test is the same as Test A.1 with the exception that some of the accelerometers are switched with one another. The

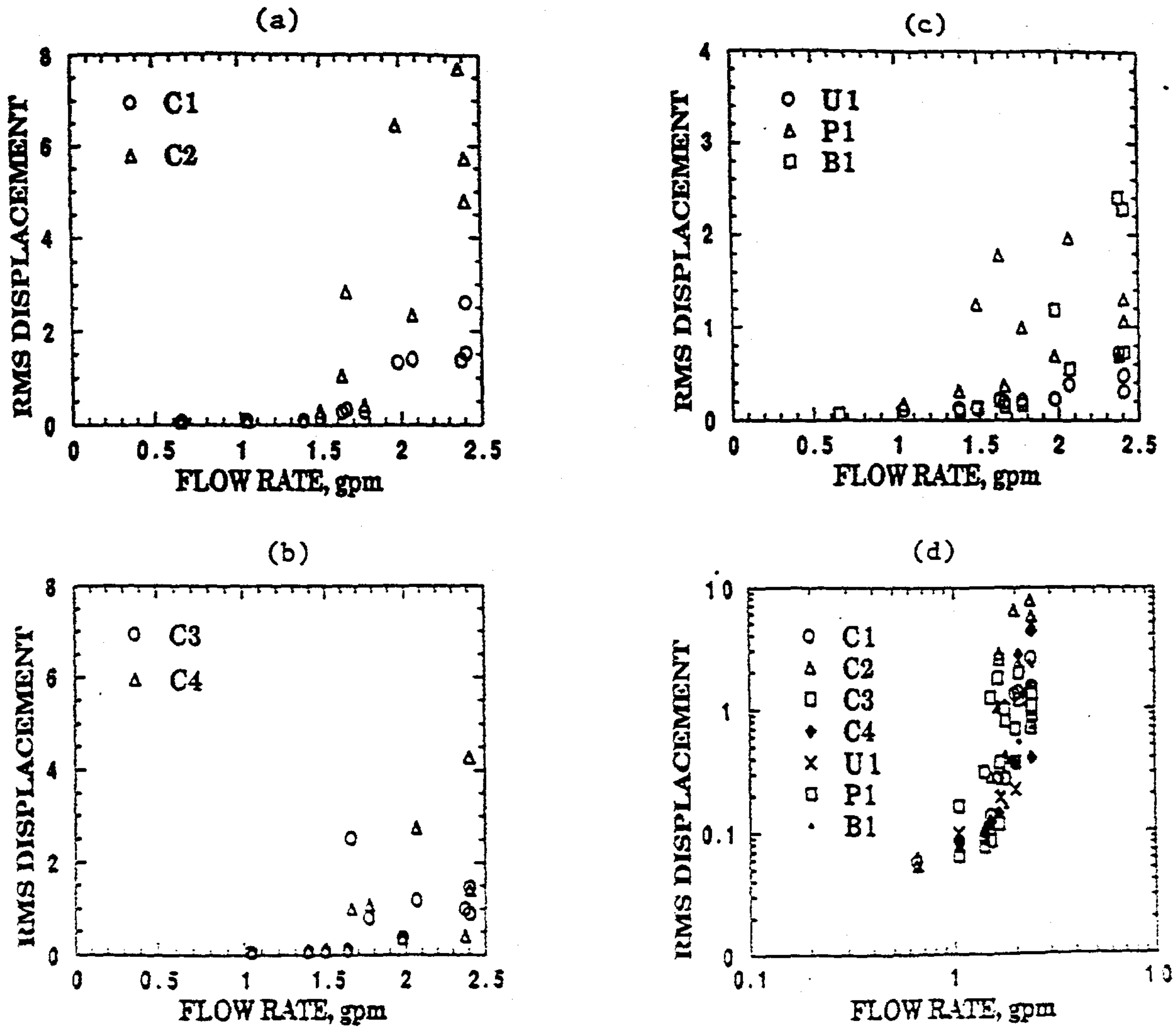


Fig. 4. RMS displacements in Test A.1; all displacement values are in μm

results are given in Fig. 5. The general trend is the same as that in Fig. 4. This reconfirms the results of Test A.1.

Test. A.3: Modifications. To understand the effect of flow and support structures, a series of tests were performed after some minor modifications were made to the crystal assembly. The following symbols are used to designate the conditions:

M1 The outlet portion of the Teflon pipe is pushed toward the south with a small steel bar to provide additional support.

M2 Both outlet and inlet portions of the Teflon pipes are pushed toward the south with a small steel bar to provide additional support.

M3 A C-clamp is used to secure the supporting plate to the support frame of the crystal mirror.

M4 A C-clamp is used to secure the supporting plate to the support frame of the crystal mirror.

N Original configuration with no modification.

The tests were performed at 2.38 gpm and 50°C. Results are given in Table 1. The effects of the minor modifications can be determined from Table 1 and are summarized below:

Pushing the Teflon outlet pipe to one side tends to reduce all responses except that at location C4, which is on the outlet connector. The additional curvature of the Teflon pipe tends to increase excitation to the connector. Reduction of crystal mirror motion is due to reduction of motion of the pipe with the additional support.

With the supports to both pipes, except at locations C1 and C2, all other responses are smaller than those when pushing the outlet pipe only.

With use of the C-clamp, displacements at all locations are reduced relative to displacements under condition N.

At the crystal mirror, displacements at locations C1, C2, C3, and C4 are significantly reduced when the pipes are supported and the C-clamp is loosely fitted.

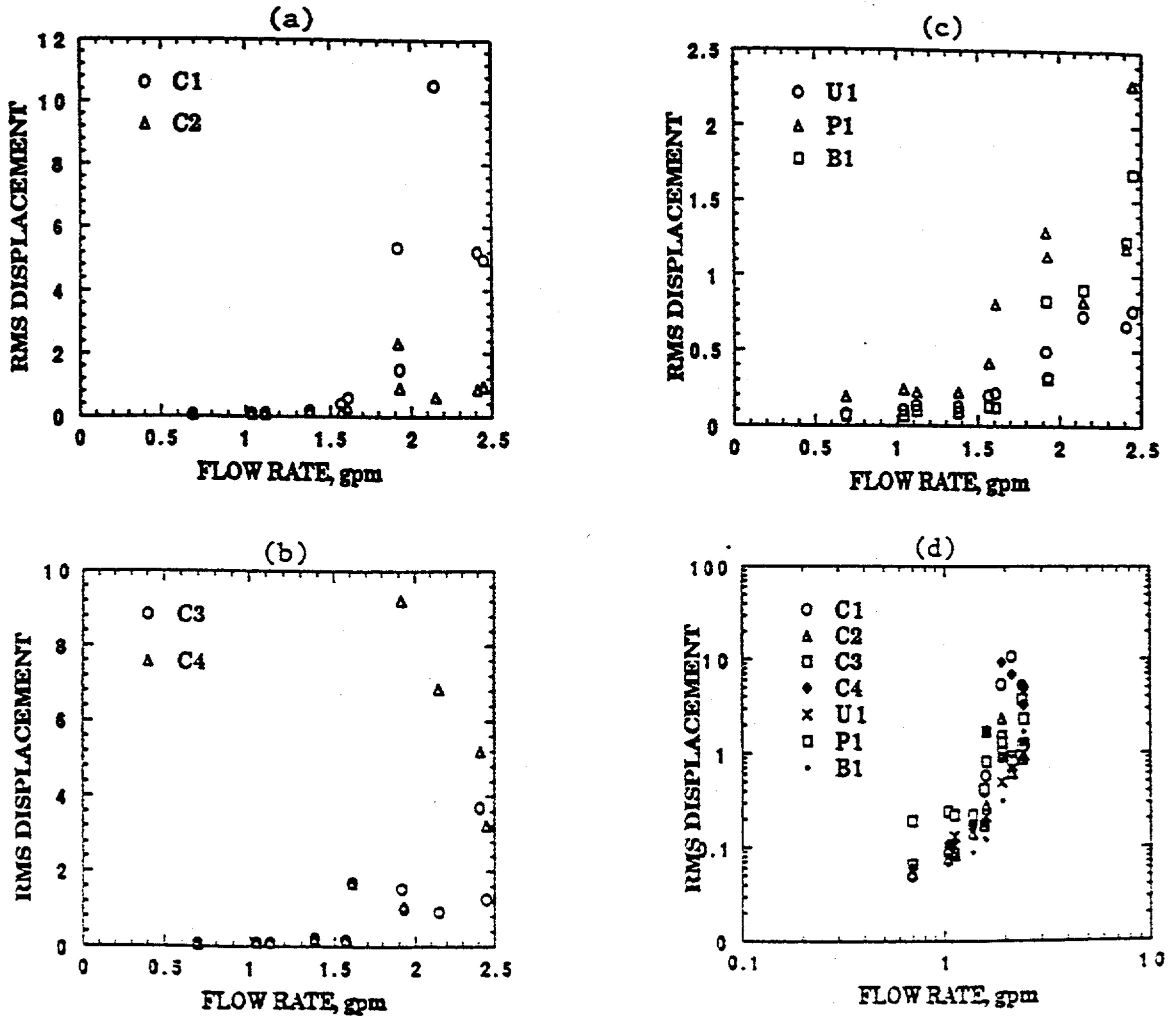


Fig. 5. RMS displacements in Test A.2; all displacement values are in μm

Table 1. RMS displacements for various conditions

Test Conditions	Location						
	C1	C2	C3	C4	U1	P1	B1
N	9.04	1.49	4.9	6.49	0.37	1.99	1.56
M1	4.98	0.77	3.66	5.01	0.34	2.28	0.95
M2	5.78	1.01	1.90	4.88	0.30	1.83	0.70
M3	6.67	1.17	1.35	3.93	0.29	1.45	0.67
M2 + M3	5.42	1.00	2.89	2.50	0.26	1.15	0.67
M2 + M4(loosely clamped)	1.45	1.15	0.41	0.74	0.35	1.23	0.26
M2 + M4(tightly clamped)	3.17	0.94	0.45	0.84	0.45	1.69	1.86

These results show that with some minor modifications to the supporting structure of the crystal assembly and Teflon pipes, mirror motion can be changed significantly. Therefore, the supporting conditions of the crystal mirror and the Teflon pipes are the critical elements in modifying the system's characteristics.

Test A.4: Effect of Temperature. Acceleration was measured at a flow rate of 2.23 gpm for two temperatures, 50° and 57°C (two tests in sequence were performed for 57°C). This test was performed following Test A.3 in time with the condition M2. The results are given in Table 2. With higher temperature, fluid viscosity is reduced. At the same flow rate, the response is reduced in general.

Test A.5: Response as a Function of Flow Rate. The motions under modification M2 were measured as a function of flow rate; results are given in Fig. 6. Several interesting characteristics are noticed:

RMS displacements increase monotonically with flow rate at all locations.

Amplitudes at locations C1 and C2 are approximately the same.

Displacements at the supports of mirror B1 and the second mirror U1 are fairly small.

Rate of increase with flow rate increases drastically as the flow rate reaches about 1.8 gpm, This flow rate is higher than those shown in Figs. 4 and 5, where the pipes are not supported by a steel bar.

While the frequency spectra of displacement and acceleration have been considered here, the detailed data are not included in this report. In general, the contributions can be divided into two groups: low frequency (<20 Hz) and high frequency (>20 Hz). The high-frequency contributions, >60 Hz, are due to excitation of structural frequencies. RMS displacements of two tests (A.5 and B.1) have also been divided into two groups, 4 to 20 Hz and 20 to 200 Hz. The RMS values of Test A.5 are shown in Figs. 7 and 8.

Comparing Figs. 6 and 7, it is obvious that the motions are due essentially to low-frequency contributions. The high-frequency contributions are very small.

Test A.6: Repeatability of General Response. The response measured at different times under the same conditions may be different. For example, under condition M2 described in Test A.3, the results shown in Table 3 were obtained at different times.
Test A.6.1 was performed first. A clamp was attached to the support of the crystal assembly and then removed. Tests A.6.2 and A.6.3 were performed in sequence after the clamp was removed. Although some variation occurs, none is significant.

Loop Configuration B

In all previous tests, the stabilizing plate was tightly connected to the support structure to prevent rotation of the crystal assembly. After all tests with loop configuration A were completed, one end of each of the two Teflon pipes connected to the crystal assembly was switched to set up configuration B. Three tests were performed:

Test B.1: General Response with Stabilizing Plate. Displacement was measured as a function of flow rate; results are given in Fig. 9. A comparison of Figs. 6 and 9 shows that except for the response at location C4, all RMS displacements in Fig. 9 are smaller than those in Fig. 6. This means that loop configuration B provides less excitation to the crystal assembly. A drastic increase in response with flow rate also occurs at about 1.8 gpm.

Test B.2: General Response without Stabilizing Plate. In all previous tests, the stabilizing plate to the crystal assembly was used; i.e., it was tightly connected to prevent rotation of the crystal assembly. In this test and in Test B.3, the plate was loosened. The effects of the stabilizing plate do not affect the response significantly.

Test B.3: General Response without Stabilizing Plate and with Additional Gallium Pressure. In all previous tests, the gallium loop was operated under ≈15 psi of vacuum. In this test, 10 psi of pressure was added to the loop. Except for the response of the outlet connector, the effects are small.

Table 2. RMS displacements at different temperature

Temperature (°C)	Location						
	C1	C2	C3	C4	U1	P1	B1
50	3.77	4.95	5.44	1.95	0.75	3.26	0.72
57 (Test 1)	3.62	2.45	1.04	1.46	0.29	1.23	0.84
57 (Test 2)	3.91	3.08	0.71	0.96	0.36	1.56	0.69

Table 3. RMS Displacement (Test A.6) under condition M2 of Test A.4 (μm)

Test	C1	C2	C3	C4	U1	P1	B1
A.6.1	5.78	1.01	1.90	4.88	0.30	1.83	0.70
A.6.2	6.85	1.49	1.98	3.74	0.40	1.74	0.34
A.6.3	5.06	1.87	2.24	3.50	0.32	2.25	0.52

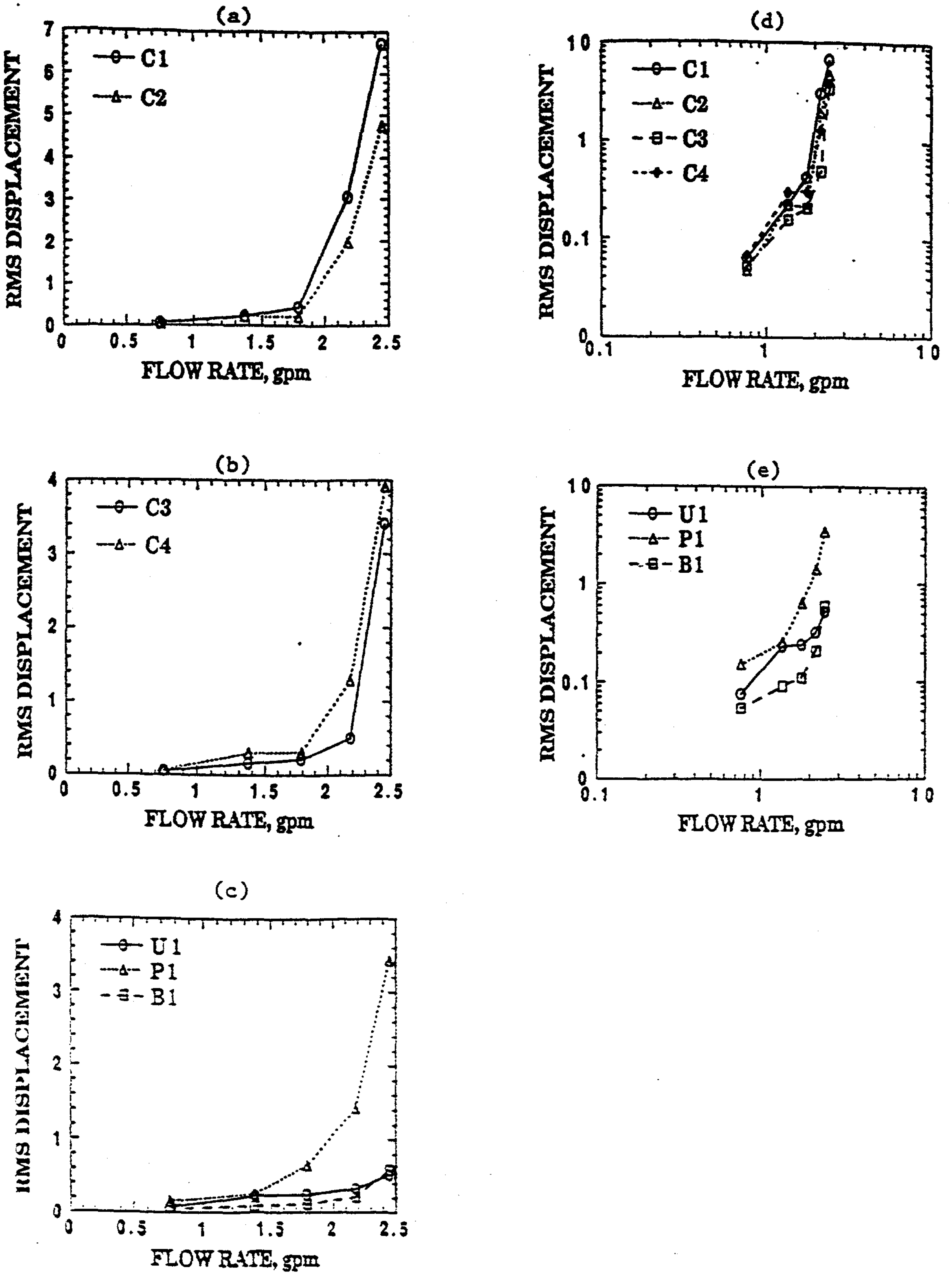


Fig. 6. RMS displacements in Test A.5, 4-200 Hz; all responses are in μm are shown in both linear and logarithmic scales

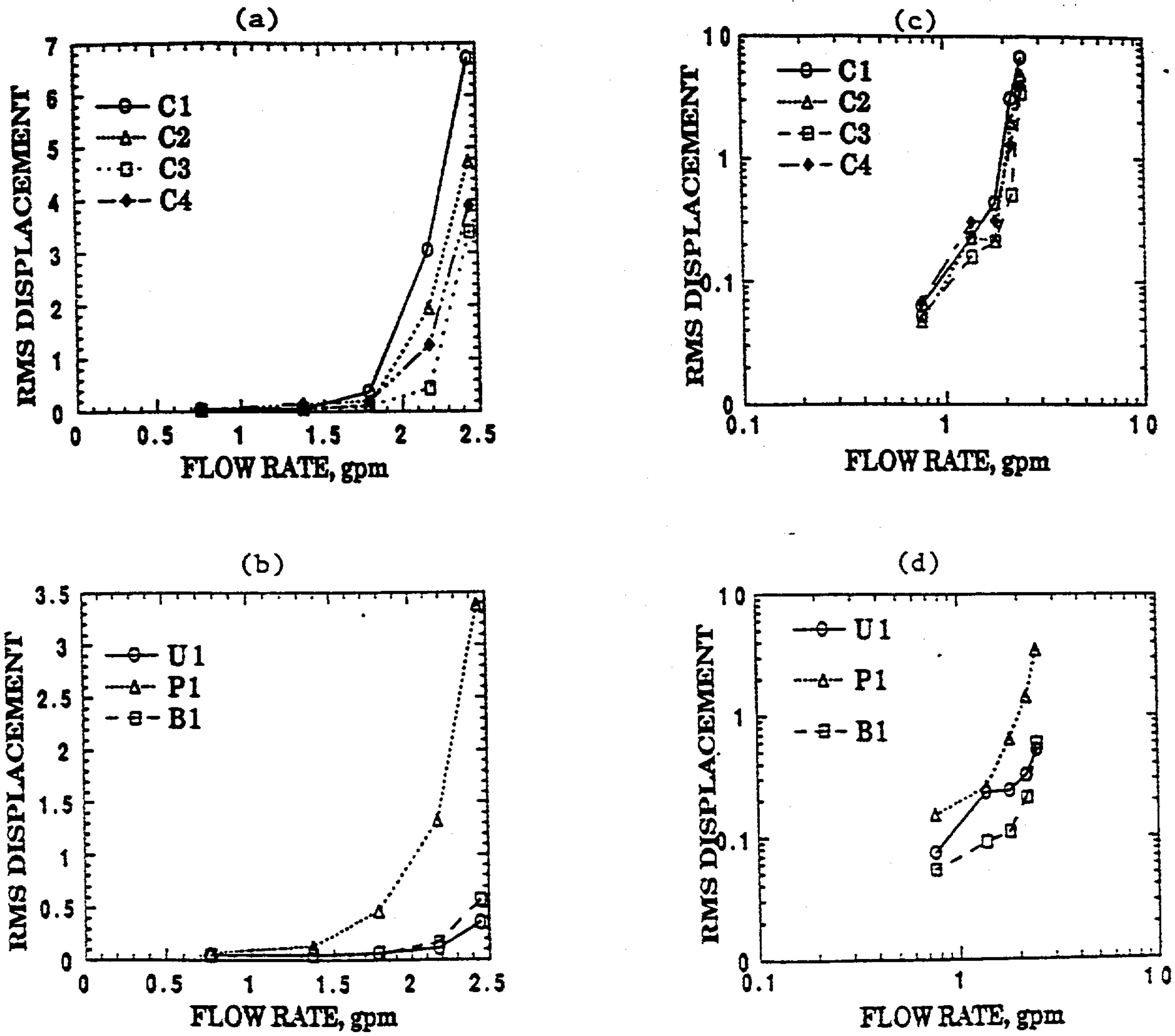


Fig. 7. RMS displacements in Test A.5, 4-20 Hz; all displacement values are in μm

Assessment of Root Cause and Abatement of Vibration

Based on the test results, the main excitation source is identified as the gallium flow. It is well understood that flowing fluid is a continuing source of energy that can excite structural vibrations (4). Once gallium is flowing, the crystal assembly and other components will vibrate continuously. There are several excitation mechanisms:

Turbulence: The turbulence of gallium passing through the mirror will excite the crystal assembly.

Flow Excitations Associated with Bends and Discontinuities in Pipes: Any bends, as well as discontinuities such as connectors, will induce both steady and unsteady fluid forces.

Motion-Dependent Fluid Forces: Any pipe motion will induce additional motion-dependent fluid forces such as centrifugal fluid forces and Coriolis forces.

Cavitation: Fluid noises associated with cavitation will excite structure vibration.

Fluid Transients: Any fluid transient will be transmitted to the crystal assembly and induce vibration.

Under certain conditions, all of these mechanisms may exist. Without additional detailed tests or data on flow loops, it is difficult to quantify the effects of each detailed mechanism in this system.

The purpose of this study is to identify the excitation source, which we have determined to be the gallium flow. The next step is to provide some guidelines for alleviating this vibration problem. We can achieve this by assessing the experimental data obtained in this study.

Loop Configurations A and B

The RMS displacements with configuration A are larger than those with configuration B. The difference

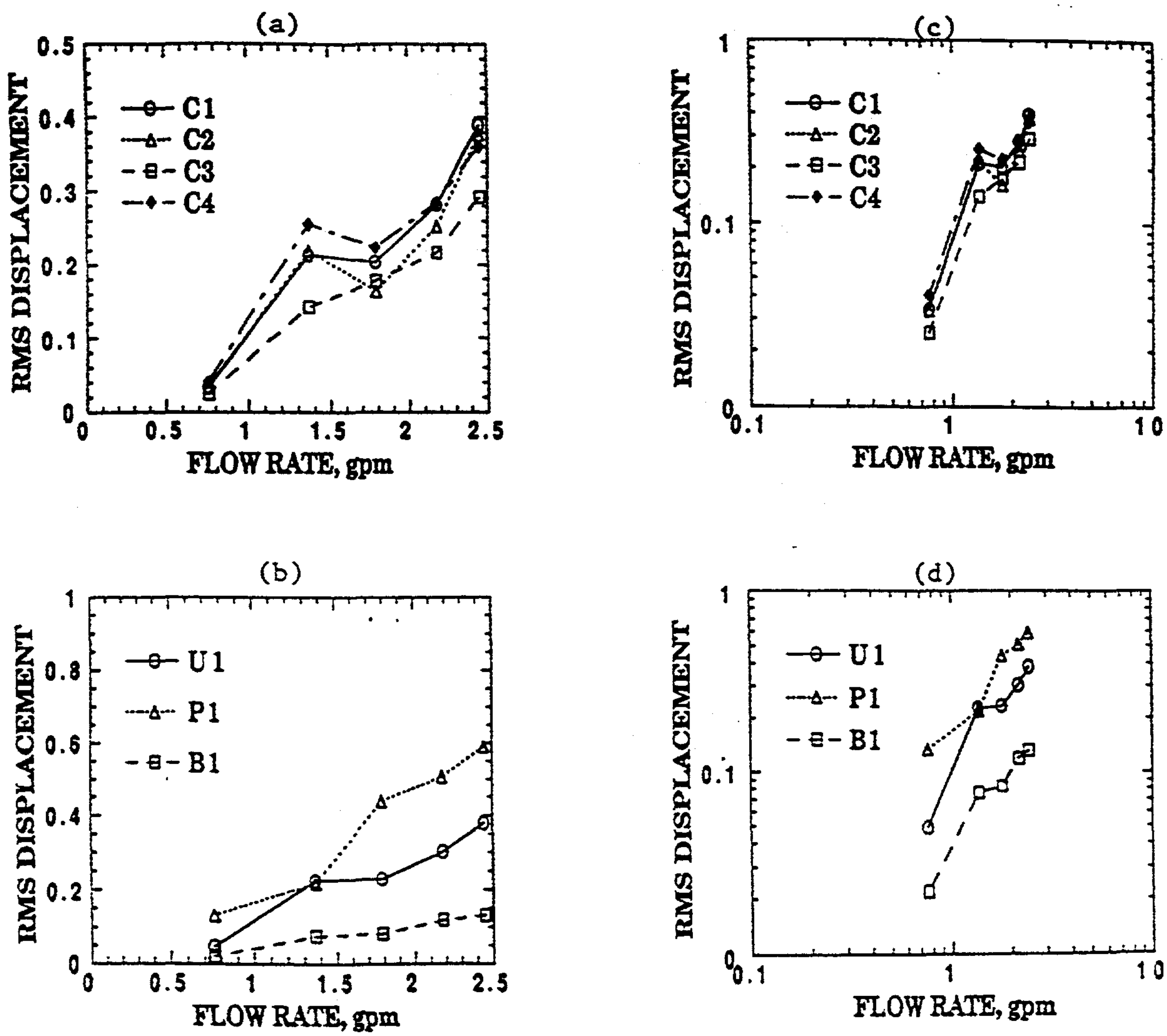


Fig. 8. RMS displacements in Test A.5, 20-200 Hz; all displacement values are in μm

is in the flow path and configuration of the Teflon pipes. In configuration A, the Teflon pipes are hung loosely while in configuration B, the Teflon pipes have higher tension and less curvature. The centrifugal forces due to gallium flow in configuration B will be lower than those in configuration A. In configuration A at high flow rate, vibration of the Teflon pipes can be seen clearly. This is likely due to the centrifugal force of the gallium flow in the Teflon pipes. The force per unit length acting on the pipe is proportional to MU^2, where M is the mass of gallium inside the pipe and U is the flow velocity. Once the pipe begins to vibrate, additional centrifugal force is induced in the gallium and part of this force is also proportional to MU^2. For example, for a straight pipe, there is no centrifugal force; however, once the pipe begins to vibrate, additional fluid forces, $M[(\partial/\partial t) + U(\partial/\partial x)]^2 y$, are induced, where t is time, x is the axial coordinate of the pipe, and y is the pipe displacement (4). This force can have several effects: changing the natural frequencies of the pipes, causing instability, and producing nonclassical normal modes. In any case, under configuration A, the pipe is much less stable. This is why the motions under configuration A are much larger; in this case, vibration of the Teflon pipes is a main excitation source to the crystal assembly.

Modifications under Configuration B

From the RMS displacements and power spectra of the displacements and accelerations, it can be concluded that:

The large motions are associated with the low-frequency contribution (<20 Hz). For a specific location, when the amplitudes are large, the contribution from the higher frequency range (>20 Hz) can be ignored.

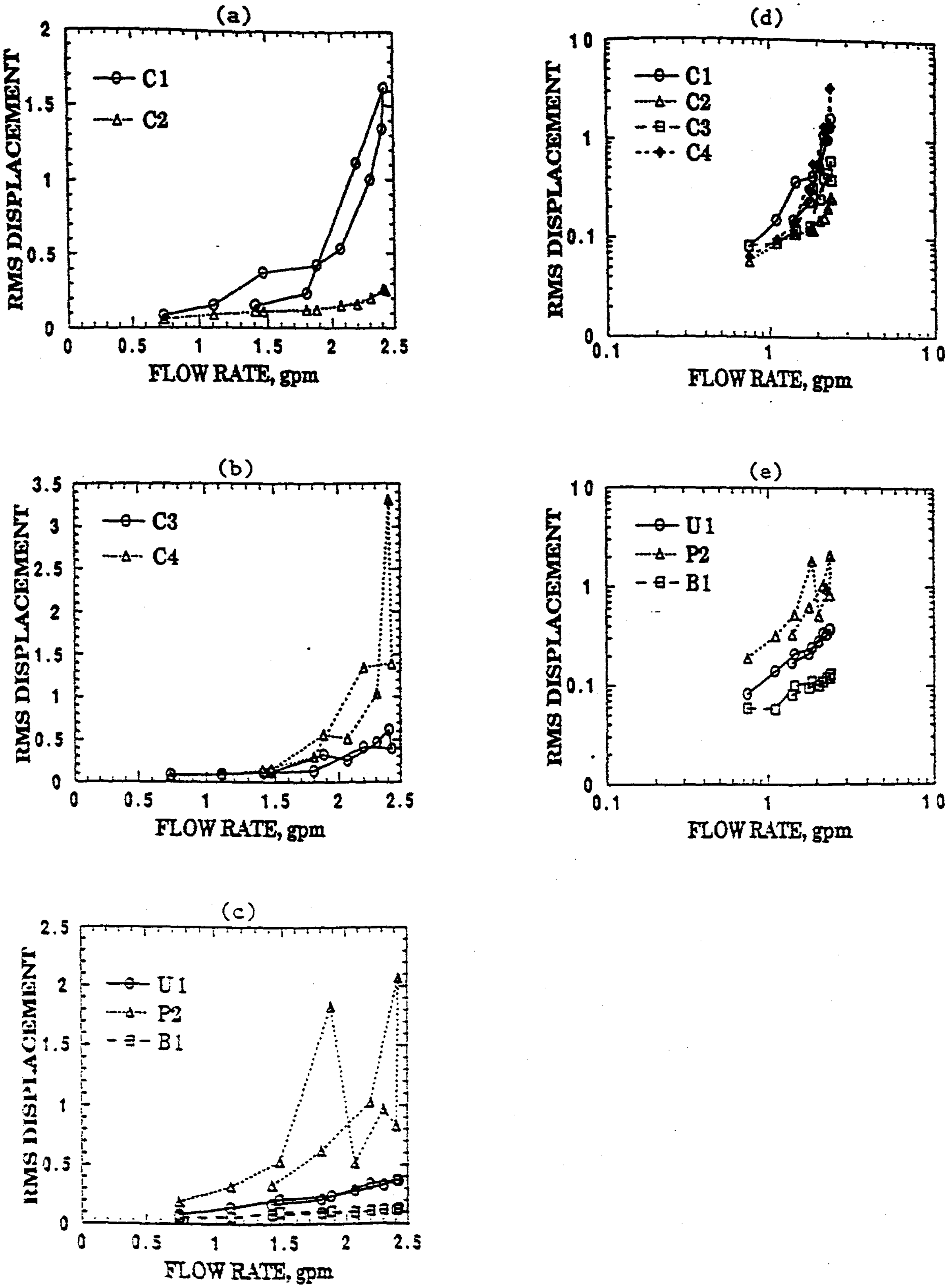


Fig. 9. RMS displacements in Test B.1, 4-200 Hz; all displacement values are in μm

When the supports to the Teflon pipes and the crystal assembly are modified slightly to improve rigidity, the response is reduced significantly and the low-frequency contribution declines.

At the support, location B1, motion from the low-frequency contribution is much smaller in general.

From the test results based on the various modifications in Test A.3, we can conclude that additional supports to the Teflon pipes and supporting plate of the mirror will reduce the response. This means that the supports to the Teflon pipes and crystal assembly can be improved to reduce the vibration amplitudes.

Excitation Mechanisms

It would be useful to determine the excitation mechanisms under various conditions, but this would require a series of detailed studies. At present, however, it is more important to develop a method for eliminating large vibration. Therefore, the key question is why the large motions occur once the flow rate reaches a certain value. Are they due to forced vibration or to dynamic instability? For example, Fig. 7c shows that when the flow rate is >1.8 gpm, amplitudes are proportional to U^7. At flows <1.8 gpm, amplitudes are proportional to U^2. Therefore, 1.8 gpm can be considered as the critical flow velocity for Test A.5. If the system is stable, response should be proportional to U^2.

The reason for the instability can be explained. When the flow rate is <1.8 gpm, the system is stable; this means that all supports are adequate. The input/output ratio of gallium energy to the crystal assembly does not vary with flow rate. As soon as the flow rate reaches 1.8 gpm, the system characteristics change such that the input/output ratio of gallium energy to the crystal assembly varies with flow rate. This means more energy is put into the crystal assembly to cause its large oscillations. The possible mechanisms may be:

Gallium fluid forces acting on the crystal assembly vary with flow rate. As flow rate increases, the support conditions vary with flow rate and consequently the system characteristics also change. When the system characteristics change, more energy from the gallium flow will be absorbed by the crystal assembly, resulting in large motion. The change in system characteristics is due to the change of boundary conditions because other parts are fairly rigid and supports are loosely connected.

Gallium flow inside the crystal assembly may cause large structural motion under certain conditions.

The cause is probably the change of support conditions due to fluid forces. For example, consider the gallium flow passing through the crystal assembly. Assuming that the inlet area is fixed, this means the input energy is constant (proportional, of course, to U^2). If the outlet area is allowed to move in a certain way, flow energy output may be lower than that of the input. The lost energy will excite the vibration of the crystal assembly. On the other hand, if the outlet is moving in a different pattern, flow energy may not be absorbed by the crystal assembly and instability will not occur.

Based on these considerations, it is obvious that the critical element is support of the crystal assembly. Due to the lack of support rigidity, fluid forces may cause a change in the support condition as the flow rate increases. Because of this change, the gallium flow is a continuing source of energy that causes significant vibration of the crystal mirror.

Conclusions and Recommendations

The small ambient motions at the crystal assembly, monochromator, and pump always exist. Sources of excitation include ground motion, pumps, gallium flow, and other mechanical sources. Based on this setup, we have identified the main excitation source as the gallium flow. Excitation levels due to other sources are much lower than those of the gallium flow. The most critical elements are the support to the crystal assembly and the pipes connected to the crystal assembly.

The critical portion is the crystal assembly itself. Its vibration level is higher than that at every other location except the pipes themselves. Because the crystal assembly is the most easily changed component, the vibration can be reduced with proper modifications.

The following general guidelines are recommended in the modification of the system to reduce the vibration level:

Anchor the crystal assembly as rigidly as possible.

Keep the pipes as smooth as possible, avoid sharp turns, and eliminate discontinuities.

Anchor the inlet and outlet pipes as rigidly as possible to prevent their vibration. In the flexible portion, reduce the unsupported length.

Prevent fluid transients and cavitation.

Avoid or reduce any flow excitation that excites the crystal assembly directly or indirectly.

Some specific changes can be considered:

Change the direction of the inlet and outlet so there is no change in flow direction. For example, if both incoming and outgoing gallium flows are in the axial direction without the 90° turn, the steady fluid forces acting on the support structure are expected to be lower.

Provide support to the connectors of the pipes so the forces will not be transmitted to the crystal mirror.

Eliminate the rocking motion (the mirror support plate can rotate about the diagonal line AC with a small force).

Provide additional support to the flexible pipes.

Increase rigidity of the supporting structure to the crystal assembly.

Many additional tests can be performed to quantify detailed characteristics of the crystal assembly. However, those are not the objectives of this study. At this time, we recommend that modifications to the support of the crystal assembly and Teflon pipes be considered to avoid degrading mirror performance. Once the new support structures are complete, tests can be conducted again to verify that vibration of the crystal mirror is within the acceptable level provided by APS under normal flow conditions.

12

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