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Aerial Camera Vibration

More effort should be made to improve vibration isolation characteristics of camera mounts as the most promising way of improving image sharpness of the aircraft-camera-film system.

Abstract: *Angular vibration of aerial survey cameras is a major direct or indirect cause of limited image sharpness. The effect is direct if a shutter speed is chosen at which image motion due to vibration is significant during the exposure. It is indirect if, to avoid blurring due to image motion, a high shutter speed is chosen which necessitates the use of a large lens aperture and/or a high speed film, either or both of which reduce system resolution.*

Measurements of vibration of modern aerial survey cameras in a variety of aircraft over the last few years have shown maximum angular velocities in the range 10 to 50 milliradians per second (mr/s). These values correspond approximately to 2 to 10 millimetres per second (mm/s) at the film for common cameras. To limit image motion due to vibration to 15 micrometres (μm) requires a shutter speed not slower than 1/130 to 1/660 s. Two comparisons are informative: (1) Image velocity due to forward motion in high altitude photography is typically 1.2 to 2.2 mm/s; and (2) measurements made 30 years ago on reconnaissance camera mounts showed an image velocity of 25 mr/s maximum for a standard mount, and 2.5 mr/s for an experimental mount.*

Camera mounts subjected to controlled linear vibrations in the laboratory developed objectionable angular vibrations with amplitude peaks occurring mainly in the frequency range 3 to 11 Hz. Inadequate vibration isolation has three causes. Mount forces do not act at or symmetrically about the center of gravity, springs are too stiff, and damping is insufficient.

If survey mounts could be developed to consistently reduce maximum angular vibration velocities to 5 mr/s or less, vibration would cease to be a practical limitation in present conditions and system resolutions could improve by 35 to 55 percent.

Introduction

The adverse effects of image motion on photographic image sharpness must have been known for as long as there has been photography. Before the First World War the British Admiralty had a problem with stable orientation of motion picture cameras in aerial balloons (Samuelson, 1967). Many workers (Carman, 1951b; Fish, 1958; Attwell, 1959; Trott, 1960; Casper, 1964; Maune, 1970; Carman, 1973) have since discussed the problems of aerial camera motion and suggested remedies. However, practical efforts to minimize image motion in civilian aerial survey photography still leave much room for improvement, although some progress has been made.

This report will point out the resolution loss being experienced, describe techniques for the study of vibration of cameras in flight, summarize results of a number of flight tests, and present results of mount tests under controlled vibration conditions in the laboratory. Some shortcomings of anti-vibration mounts will be discussed and improvements will be suggested.

* See Appendix A

Present Resolution Losses

The loss of image sharpness and resolution that can occur from excessive image motion is generally understood and generally avoided by the use of high shutter speeds. That this use of high shutter speeds causes, indirectly, a loss of image sharpness does not seem to be as widely understood.

If image motion did not have to be controlled by high shutter speeds, it would be possible to achieve immediate gains on the order of 35 to 55 percent in resolving power. Consider Figure 1,

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replotted from a study of resolution in a 15-cm focal length, 23- by 23-cm format, survey camera (Carman, 1970). If, instead of having to use Kodak Double X film (DX) at *f*/5.6 to obtain adequate exposure at a high shutter speed (e.g., 1/890 s), it were possible to use Plux X (PX) at *f*/11 and 1/150 s or Panatomic-X(FX) at *f*/11 and 1/65 s, area weighted average resolution at the optimum scene brightness in the representative range would increase from 18 mm^{-1} to 24 mm^{-1} or 28 mm^{-1}, respectively. (Resolution values are for an annulus resolution target with a realistically low contrast of 0.20 log luminance ratio. This target has been preferred in Canada for closely representing practical use and for avoiding artificial emphasis on special directions (Howlett, 1946). It gives numerical values lower than those for two-line or three-line targets.) Considering resolution averages over the representative scene brightness range weighted by the typical distributions in that range (Carman, 1951a), corresponding values would increase from 17 mm^{-1} to 23 mm^{-1} or 27 mm^{-1}. Such a gain in resolution could be applied to improve picture quality or to reduce photo scale or to a combination of the two. The economic gain from improved picture quality would be real in terms of interpretation time and accuracy, but would be hard to evaluate quantitatively. However, it is simple to evaluate the possible effect of reducing scale to just maintain the same ground resolution. For the two steps of improvement mentioned, photo line miles would be reduced to 75 percent or 64 percent of the value with DX, *f*/5.6, and 1/890 s, and the number of photographs to 56 percent or

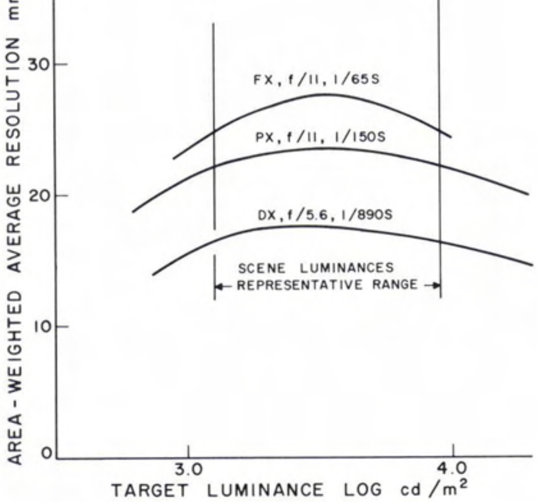


FIG. 1. Area weighted average resolution of a survey camera of 15-cm focal length and 23 by 23-cm format for a range of luminances of low contrast annulus tarets.

41 percent. It thus seems reasonable to conclude that considerable economic gains could be achieved by a serious study of image motion and development of better methods for reducing it.

FLIGHT TESTS

METHODS OF MEASURING CAMERA VIBRATION IN FLIGHT

The technique of measuring the angular vibration of an aerial camera by flying over lights at night with the camera shutter open appears to have originated in England during the Second World War. Of course, none of their reports were published. Their techniques were communicated to the National Research Council in Canada and similar tests were begun there. The wavy lines drawn on the film by steady lights, as used initially, permitted only evaluation of angular vibration in roll, i.e., about the fore and aft axis of the aircraft. By replacing the steady lights with two lights flashed rapidly and in synchronism at an accurately known rate, the possibility of measuring pitch and yaw components was added. This was first done with lights flashed by means of rotating sectors, as reported in 1951 (Carman, 1951b).

When similar studies were resumed much more recently, electrically flashed discharge lamps were substituted. General Radio Stroboslaves were used with their concentrating reflectors removed in order to provide a source uniformly visible over a wide angle and to make the source size small enough so that its image in the camera would be as small as possible. Used in this way at 300 flashes per second, the Stroboslaves had only enough intensity to permit good imagery for a 153-mm focal length, *f*/5.6 lens, if the aircraft was flown at about 400 feet above ground. Such a low altitude complicated flight operations because of air traffic control regulations. To avoid this difficulty, the optical system shown in Figure 2 was designed, and three were built. They concentrate practically all the light from the flash tubes in an upward cone of 31° semi-angle and permit operation at 1000 feet above ground with ample image density on the negatives.

Subsequently, to permit testing of inertial systems for recording camera position and orientation, arrangements were made to synchronize the flashing lamps to the CHU Canadian time signals, with the third lamp added to provide enough data to permit calculation of the six elements of exterior orientation of the camera at each flash.

MEASUREMENT DIFFICULTIES

This method of measuring angular motion of cameras in flight has several disadvantages which should be mentioned. (1) The ground installation is fixed, requiring the aircraft to come to it. (2) The ground operation is costly in man-hours. (3) Flying conditions are not typical of aerial survey op-

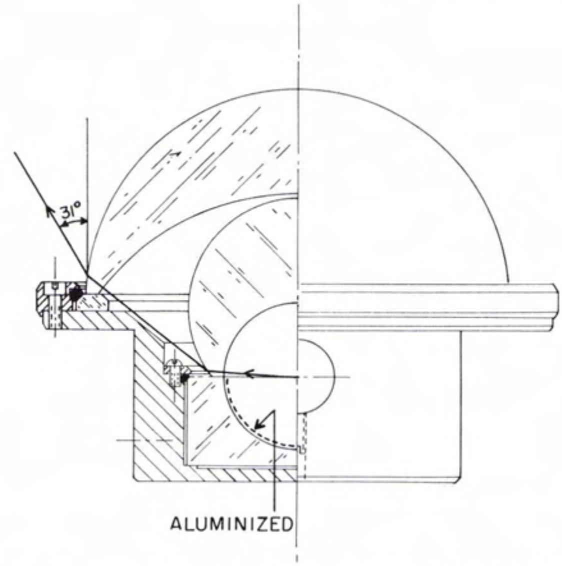


FIG. 2. Optical system for Stroboslave electronically flashed lamps.

erations. The low altitude means denser air and hence different aircraft attitude and engine settings. It does not give significant increases in turbulence because in night flying smooth conditions are easily found. (4) Data analysis is time-consuming and hence the length of time sampled is small. (5) Accuracy is limited by pointing accuracy on the images of the point light source on the film, with granularity a significant factor. (6) Accuracy of angular velocity values can be improved by increasing the time between flashes, but data on high frequency vibrations may be lost. If an alternative convenient measuring method could be developed, based on instrumentation which could be used in an aircraft without a ground reference, it would be most helpful in improving knowledge of vibration problems. Worton (1981) indicates some progress in this direction.

RESULTS OF FLIGHT TESTS

Figures 3 and 4 show in graphical form some examples of vibration data obtained in flight tests. All cameras were of 15 cm focal length and 23- by 23-cm format. The plots are of angular *velocities* of the camera about three mutually perpendicular axes—roll, pitch, and yaw—as a function of time. Each graph is based on 127 flashes of the lights, i.e., 126 time intervals each of 1/300 second. "Fast" indicates a run made at the speed normally used for photographic work. "Slow" indicates a situation representative of slow flight such as would be used to reduce image motion due to forward motion of the aircraft.

Figure 3 applies to a Falcon aircraft with two rear-mounted fan-jet engines carrying two Wild

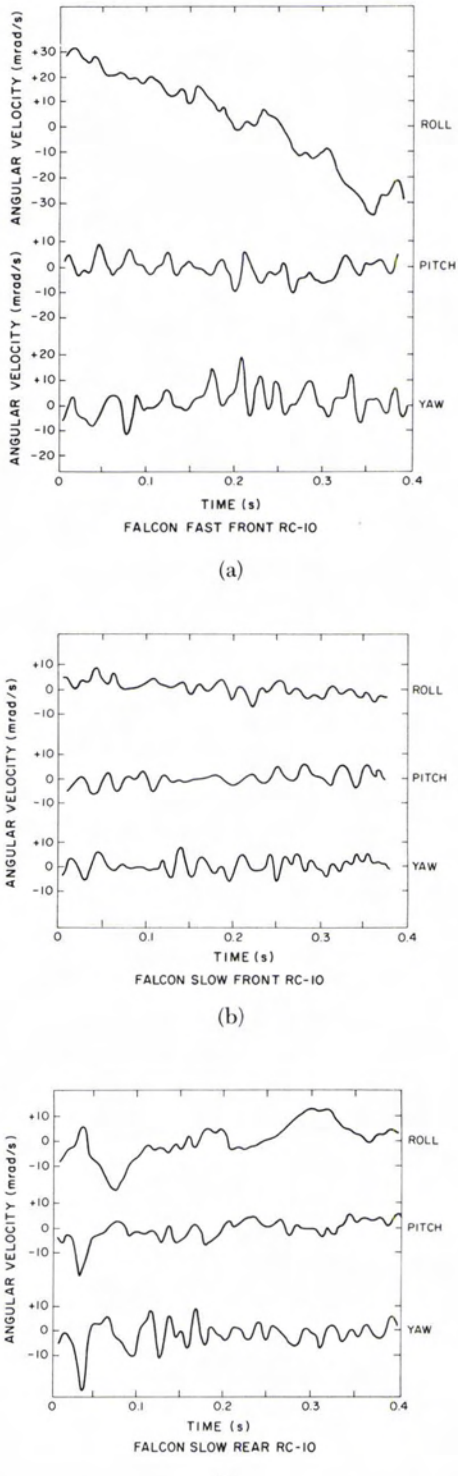
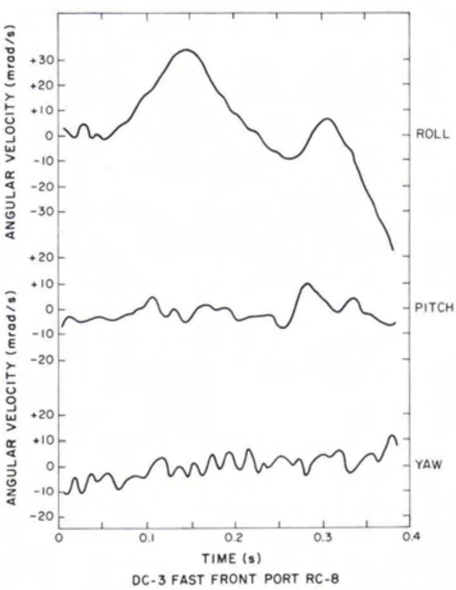


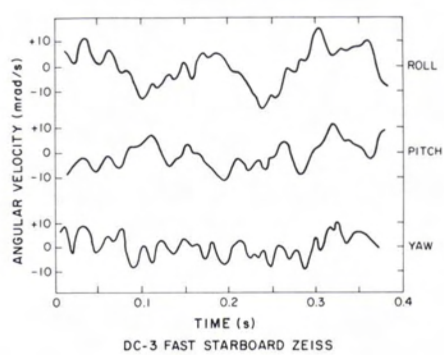
FIG. 3. Angular velocities found for Wild RC10 cameras in a Falcon jet aircraft, for two aircraft speeds and two camera positions.

RC-10 cameras in a front and a rear position. Figure 3a is for "fast" operation. The gross slope of the "roll" curve can probably be disregarded as a test artifact due to the aircraft not having entirely settled down after maneuvers to get on course over the target lights. Figure 3b is for "slow" operation and the same "front" camera. All three vibration velocities are considerably less than in Figure 3a. Lower vibration at lower speed is quite apparent for this jet aircraft. Such an effect has not been found significant in slower, piston-engined aircraft. Figure 3c is the "slow" operation again but the "rear" camera shows much worse vibration, most noticeably a low frequency (7 Hz) roll.

Figure 4 applies to a DC-3 (Dakota) aircraft with two camera positions, a port front position used for Wild cameras RC-8 and RC-10, and a starboard aft position used for Zeiss RMKA 15/23 cameras. Figures 4a to 4c indicate some significant differences between different camera-mount systems.



(a)



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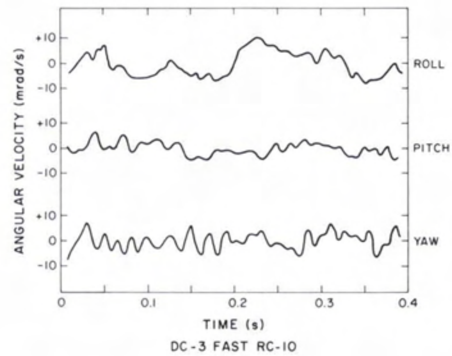

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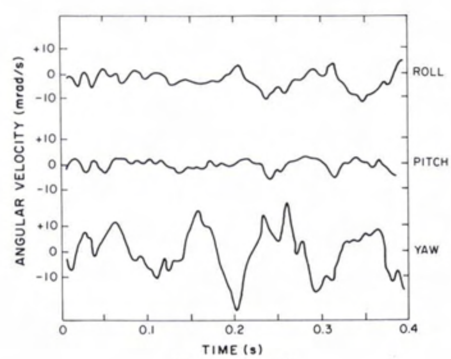

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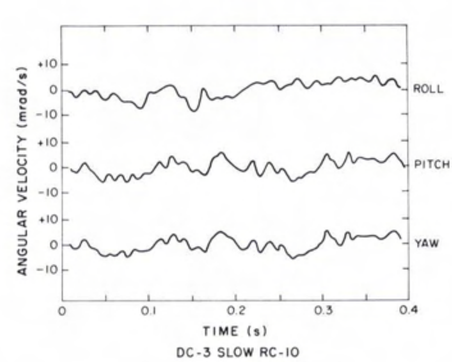


(e)

Fig. 4. Angular velocities found in a DC-3 (Dakota) aircraft for speeds, camera positions, and camera types indicated.

TABLE 1

Aircraft	Mount	Camera	Vibration Frequencies (Hz)			Maximum Image Vibration Velocities mm/s				Slowest Permissible Shutter Speed s
			Roll	Pitch	Yaw	Roll	Pitch	Yaw	Resultant	
DC-3, 2 engine, piston	{foam rubber}	F-52				5.3	2.1	10	12	1/800
DC-3, 2 engine, piston	gimbal	F-52				0.5	0.4		0.6	1/40
Light, 2 engine, piston	special	RC-5A	16	20		8	4	(2) 1	(9) 8	(1/600) 1/550
Light, 2 engine, piston	RC-8	RC-8	11	27	27	6	1	5	10	1/670
Light, 2 engine, piston	RC-8	RC-8	19	19	19	(4) 1	1	(5) 3	(8) 5	(1/550) 1/330
Light, 1 engine, piston	RC-5A	RC-5A	21, 6	21	21	6	4	3	9	1/660
Skyvan, 2 turboprop	RC-8	RC-8	35, 12	30	50, 35	(3) 2	2	(2) 1	(6) 4	1/270
Falcon, 2 jet, fast, front	RC-10	RC-10	65, 14	65, 30	65, 50, 38	(5.9) 2.2	1.9	1.8	(6.5) 3.4	(1/430) 1/230
Falcon, 2 jet, fast, rear	RC-10	RC-10	7	7	58, 38	(4.0) 1.9	2.5	1.5	(5.0) 3.5	(1/330) 1/230
Falcon, 2 jet, slow, front	RC-10	RC-10	45, 16	45, 29	45	(2.7) 1.3	1.3	0.8	(3.1) 2.0	(1/210) 1/135
Falcon, 2 jet, slow, rear	RC-10	RC-10	7	32	39	(3.8) 2.7	(3.4) 1.3	(2.3) 1.1	(5.6) 3.2	(1/380) 1/210
DC-3, 2 engine, piston, fast	RC-10	RC-8	6	35, 17	49	(8.6) 4.8	2.1	(1.3) 0.6	(8.9) 5.3	(1/600) 1/350
DC-3, 2 engine, piston, fast	Zeiss	RMKA	52, 7	39, 17	45, 10	3.1	2.3	1.0	3.9	1/260
DC-3, 2 engine, piston, fast	RC-10	RC-10	12	24	17	1.3	1.1	1.0	2.0	1/135
DC-3, 2 engine, piston, fast	RC-10	RC-10	57, 10	70, 42	54	(3.1) 2.3	1.3	1.1	(3.5) 2.9	(1/230) 1/190
DC-3, 2 engine, piston, slow	Zeiss	RMKA	55, 17	26	43, 19	2.7	2.7	0.9	3.9	1/260
DC-3, 2 engine, piston, slow	Zeiss	RMKA	34, 9	49, 19	52	(3.2) 1.9	2.3	1.4	(4.2) 3.3	(1/280) 1/220
DC-3, 2 engine, piston, slow	RC-10	RC-10	10	10	51	1.9	1.9	0.7	2.8	1/190
DC-3, 2 engine, piston, slow	RC-10	RC-10	9	6	58, 5	(2.1) 1.0	0.8	1.2	(2.5) 1.7	(1/170) 1/115
DC-3, 2 engine, piston, slow	RC-10	RC-10	53, 9	46, 13	10	2.1	1.1	2.2	3.3	1/220
DC-3, 2 engine, piston, slow	RC-10	RC-10	46	55, 9, 6	55, 9	1.5	1.1	0.5	2.0	1/130

Note 1: Bracketed values represent higher vibration velocities not considered typical of the smoothest survey flying, but of worse conditions which may arise.
Note 2: Slowest permissible shutter speeds are those required to keep image motion due to angular vibration alone down to 15 μm.

Figures 4d and 4e indicate the possibility of very different vibrations occurring under nominally identical conditions.

Table 1 summarizes results of vibration measurements from eight different aircraft and a variety of cameras, mounts, and operating conditions. The first two lines present data reported in 1951 (Carman, 1951b) for an F 52 camera, recomputed to apply to a 15-cm focal length and 23- by 23-cm format. The "foam rubber" mount was of the typical Canadian Air Force design of that time, the gimbal mount was a purely experimental mount with the center of gravity of the camera accurately at the intersection of the three axes of a gimbal system. Conversions from angular velocities to image velocities have been made on the basis of certain consistent approximations discussed elsewhere (Carman, 1973). Slowest Permissible Shutter Speeds are those required to keep image motion down to 15 μm*, assuming the angular vibration reported is the only motion. In practice, a higher speed would be needed to allow for the addition of some image motion due to forward motion of the aircraft. Bracketed values in the table represent higher vibration velocities which did not appear typical of the smoothest survey flying. They do, however, represent worse conditions which can easily arise. Vibration frequencies listed were estimated from visual inspection of graphs like Figures 3 and 4. They provide an approximate indication of troublesome frequencies. In general, where more than one frequency is given for a camera, the lower one is associated with the higher image velocities. Frequencies down to 5 Hz were encountered.

ACCURACY

Accuracy of the figures and of the data in Table 1 is difficult to estimate. Measurement of the positions of the point images is limited chiefly by film granularity, which tends to produce random errors. These are reduced considerably by some averaging which occurs in the data processing, and by attempts to apply intelligent smoothing to the hand-drawn graphs. It is believed that results are meaningful to within 2.5 mr/s on pitch and roll, to within 5 mr/s on yaw, and to within 0.5 mm/s on linear image velocities.

Conclusions from Flight Tests

Results suggest that some improvements may have been made over the years in the vibration isolation characteristics of mounts for survey cameras. For example, the RC-10 mounts in the DC-3 show about half the angular vibration velocity of the RC-8 and RC-5A mounts in the four light aircraft. Unfortunately, the effects of different mounts cannot be separated clearly from the effects of different aircraft. The RC-8 camera in the DC-3 aircraft was in an RC-10 mount with a special adapter, and the adverse effect of the mismatch is apparent.

It is clear that there is still a need for improvement in commercial mounts. The best run of the best commercial mount shows three times the angular velocity of the experimental gimbal mount built 30 years ago. Present mounts are needlessly limiting camera resolution.

Laboratory Tests

To provide information on the vibrational behavior of aerial cameras under controlled conditions of vibration, arrangements were made to test a number of different cameras and mounts on a large laboratory shaker.

The shaker provided strictly linear vibration of controlled amplitude and sinusoidal form in either a vertical (Figure 5) or a horizontal (Figure 6) direction. By choice of camera mount orientation on the shaker, the horizontal vibration could be made to correspond to either fore-and-aft or sideways vibration relative to the normal positioning of the camera in an aircraft. On the basis of preliminary tests and available data on aircraft vibration (Casper, 1964), the applied sinusoidal linear vibration was given a peak-to-peak displacement of 1 mm from 3 Hz to a crossover point at 7 Hz, above which it was controlled at 0.1 g, all as shown in Figure 7. The preliminary tests confirmed a reasonable assumption that the angular amplitudes

Fig. 5. Shaker arrangement for vertical vibration.

* See Appendix A

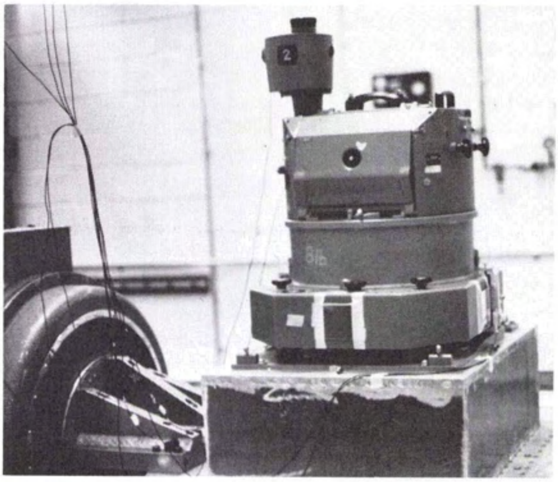


FIG. 6. Shaker arrangement for horizontal (sideways) vibration.

resulting would be approximately proportional to the applied linear vibrations.

For each of the three directions of applied linear vibration, the resulting angular vibration of the camera was measured as components in yaw, pitch, and roll. To do this, autocollimating telescopes were aimed at two plane mirrors attached to two adjacent sides of the camera by adhesive tape. A point light source 8 μm in diameter was provided in the focal plane of each collimator objective by imaging there, through a 10× microscope objective, a 2 watt zirconium arc. The light from this source, collimated by the collimator objective and reflected back to it by the mirror, was then reimaged by it through a beam-splitting prism to a filar micrometer eyepiece. The total displacement of the moving bright spot image was then measured—in the horizontal direction to correspond to yaw and in the vertical direction to correspond to roll or pitch, depending on mirror position. Collimator focal length was 464 mm so that 1-mm image motion corresponded to 2.16-mr beam rotation or 1.08-mr camera rotation.

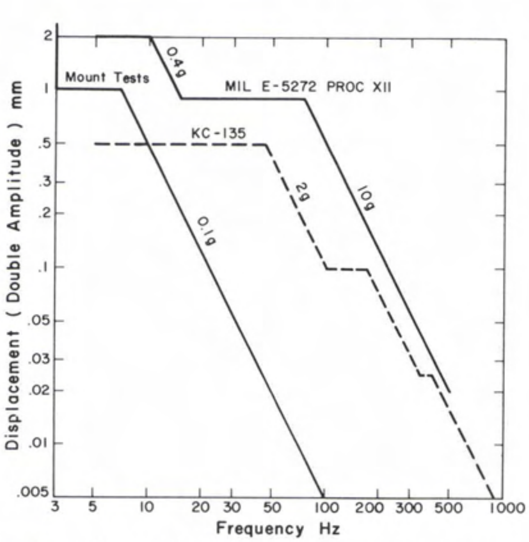


FIG. 7. Vibrational displacement used in tests versus frequency, with some aircraft vibration information.

TABLE 2. WEIGHTS OF CAMERAS TESTED

Camera	Weight kg	Center of Gravity Position Relative to Spring Center: Above mm	To Port mm	Aft mm
RC10, 153 mm	140	112	7	11
RC10, 88 mm	117	175	10	8
RC10, 153 mm, ring	144	220	7	11
RMKA 15/23	164	186	8	4
RMKA 8.5/23	208	133	16	10
MRB 15/2323	110	−10	0	12

To provide a practical weight distribution, all cameras were loaded with film divided unequally between the supply spool (aft) with a film plus spool weight of 2810 gm and the takeup spool at 1200 gm. Table 2 gives weights of cameras as tested, that is, the weight of the total system supported by the shock absorbing spring mounting, and the position of the center of gravity of that system relative to the effective center of the spring mounting. Some approximations were involved in estimating the height of the effective center of the springs and in deciding what portion of the mount weight should be included as part of the supported system.

Results will be presented, as they were measured, in terms of total camera rotation. The relationship between permissible total camera rotation and vibration frequency is given in Figure 8, for three different shutter speeds and an allowable camera rotation during exposure of 0.075 mr, which corresponds approximately to an allowable image motion of 15 μm. (The image motion for a given rotation depends on the focal length and the position of the image in the format. Considering the worst positions, a yaw of 0.075 mr produces a 12.2-μm motion in the corner of the format. Roll or pitch of 0.075 mr happens to produce about 18.0-μm motion at the edge of the format for all the three focal lengths of 85, 88, and 153 mm tested.)

Calculations of the curves of Figure 8 involved two assumptions. First, the angular vibration was considered to be simple harmonic motion at the frequency of the applied linear vibration. This was known to be the usual situation, although in a few cases harmonics did appear. Second, a worst case

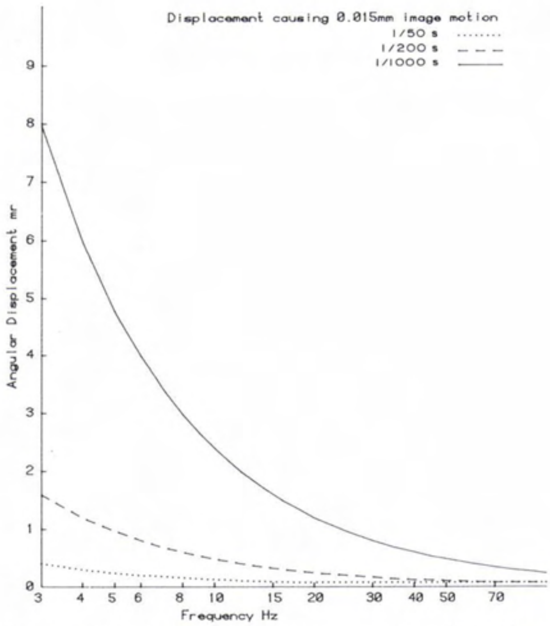
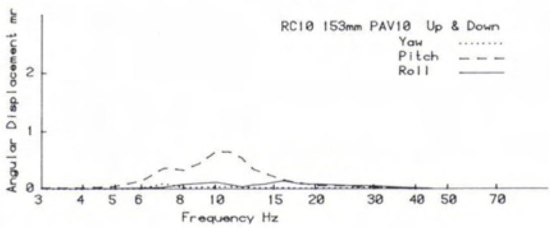


FIG. 8. Permissible total camera rotational displacement for 0.075-mr rotation during exposure times indicated versus frequency of vibration.

condition was used for the time relationship between shutter opening and vibration. That is, the midpoint of the shutter open time was taken to occur at the maximum velocity of the simple harmonic angular vibration. It should be mentioned that the angular motion during exposure thus is a fraction of the total angular motion for low frequencies, but that the two are equal for higher frequencies with vibration periods equal to or less than twice the shutter open time.

Figures 9 to 12 show the results of some of the tests on six cameras in four mounts. These figures are to the same scale as Figure 8, which can be considered as indicating tolerance levels (assuming the laboratory vibration as typical).

Figures 9a to 9c show the angular vibrational displacements of a Wild RC10 camera, 153-mm focal length, in a PAV10 mount, for respectively up-down, fore and aft, and sideways applied vibration. Isolation for up down vibration is reasonably good but the horizontal vibrations both produce serious angular vibrations due to what is often described as an "inverted pendulum" effect. The center of gravity of this camera was 112 mm above the center of its spring support system. Con-



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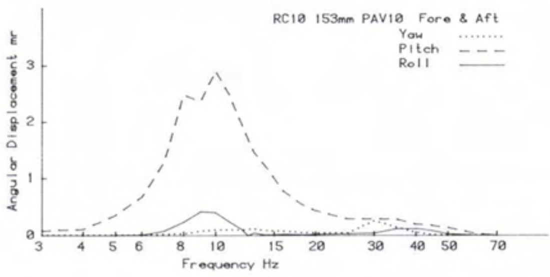

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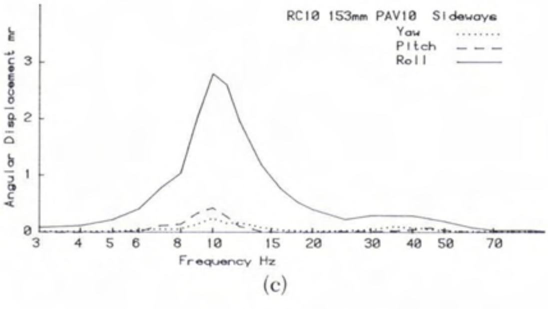

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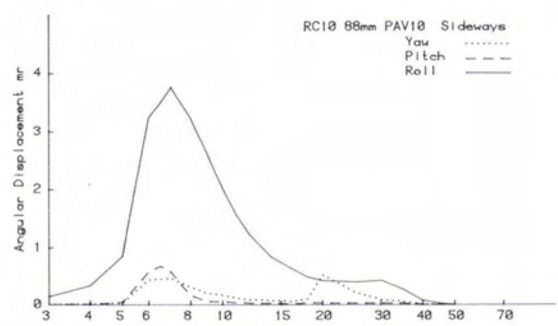

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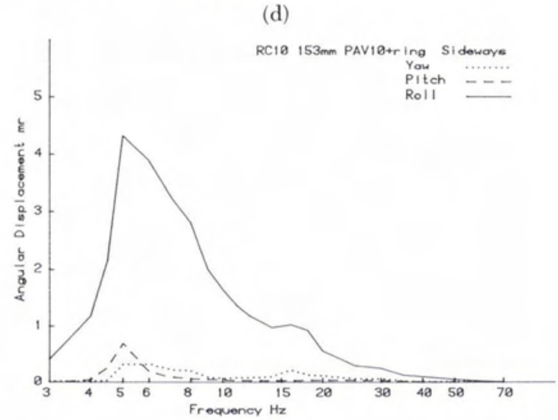


(e)

FIG. 9. Angular vibration displacements of three configurations of the Wild RC10 cameras in a PAV10 mount on laboratory shaker.

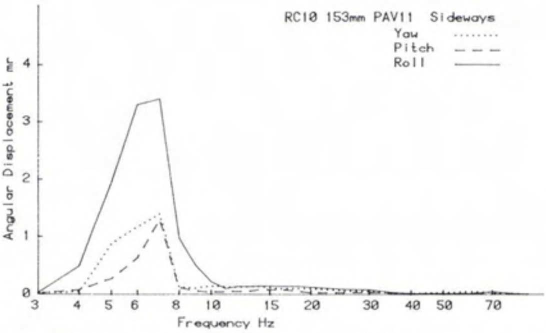


FIG. 10. Angular vibration of Wild RC10 camera in PAV11 mount in laboratory.

sequently, fore and aft vibration causes pitching and sideways vibration causes roll, with resonant frequencies causing the maximum amplitudes shown.

It should be noted that the particular PAV10 mount used had been fitted with a rubber ring enclosing the cone to limit loss of cabin pressure in the event of a port glass failure. This ring undoubtedly affected the mount performance somewhat. The PAV11 mount discussed below did not have such a ring (Figure 10).

All RC10 tests showed the same characteristic of good performance on up-down vibration, with sideways and fore-and-aft results similar to one another. Consequently, only sideways results will be given for the three other RC10 configurations.

Figure 9d shows results for sideways vibration of the RC10 with 88-mm focal length in the same PAV10 mount. The larger center of gravity height of 175-mm correlates with increased maximum roll occurring at a lower frequency.

Figure 9e shows the same results for the RC10 with 153-mm focal length mounted with an adapter ring. This ring is used to raise the camera in the aircraft without moving the mount, in order to obtain the same clearance between the cone and the camera port glass as with the 88-mm lens. It increases the center of gravity height to 220-mm, with a further increase in maximum roll occurring at a still lower frequency.

Figure 10 shows the RC10 in the newer PAV11 mount. Comparison with Figure 9c shows that the peak, although slightly higher, is at lower frequency. High frequency isolation is better. Considering the shape of the tolerance curves of Figure 8, the newer mount performed better.

Figures 11a to 11c show results for the Carl Zeiss Oberkochen RMKA camera of 153-mm focal length. It shows serious angular vibration arising when up-down linear vibration is applied. For the two horizontal vibrations, it is noted that considerable angular vibrations occur down to the lowest test frequency (3 Hz).

The RMKA of 85-mm focal length (Figures 11d to 11f), in a different mount from the 153-mm focal length, shows general similarities with some differences. The relative magnitudes of fore-and-aft and sideways effects have interchanged. Behavior at 3 Hz is better. Performance generally is somewhat better, perhaps associated with the lower center of gravity. It is noted that this camera shows the most yaw, relative to pitch and roll. This may be partly due to its center of gravity being furthest horizontally from the spring center.

Figures 12a to 12c show results for the Zeiss Jena MRB 15/2323 camera of 153-mm focal length. The camera itself is shown in Figure 13. This camera is interesting because an obvious effort has been made to put the support springs at the same height as the center of gravity. The support springs are in the three cylindrical posts. They are rubber in shear. The design has achieved very good isolation at low frequencies (3 to 5 Hz) but shows resonances above that (7 to 9 Hz). This could be related to insufficient damping. The better behavior in fore-and-aft vibration than in sideways vibration is probably related to the fact that the three supports are spaced more widely in the fore-and-aft direction than in the sideways direction.

Conclusions from Laboratory Tests

All the mounts tested convert linear vibration to angular vibration and in doing so act at some frequencies as vibration amplifiers rather than as vibration absorbers. This amplification is due to the fact that the mounts have natural frequencies of vibration at which they are not sufficiently damped. Consequently, they resonate and increase vibrations at or near these frequencies.

The amplitude of angular vibration is increased as the center of gravity of the supported camera system becomes further away from the effective center of the spring supports, for otherwise similar systems.

Recommendations

More effort should be made to improve vibration isolation characteristics of camera mounts as the most promising way of improving image sharpness of the aircraft-camera-film system. An anti-vibration mount cannot be considered satisfactory as long as vibration, rather than image motion due to ground speed, is the limiting factor in choice of shutter speed. Image motion due to ground speed, in high altitude photography for mapping, may be 1.2 to 2.2 mm/s. This suggests, as a minimum goal, a mount which could consistently keep image velocities due to vibration down to 1 mm/s. This would permit shutter speed as low as 1/67 s for 15 μm image movement. It corresponds approximately to an angular velocity of 5 mr/s and requires that at the higher frequencies, above about 33 Hz, the total angular displacement

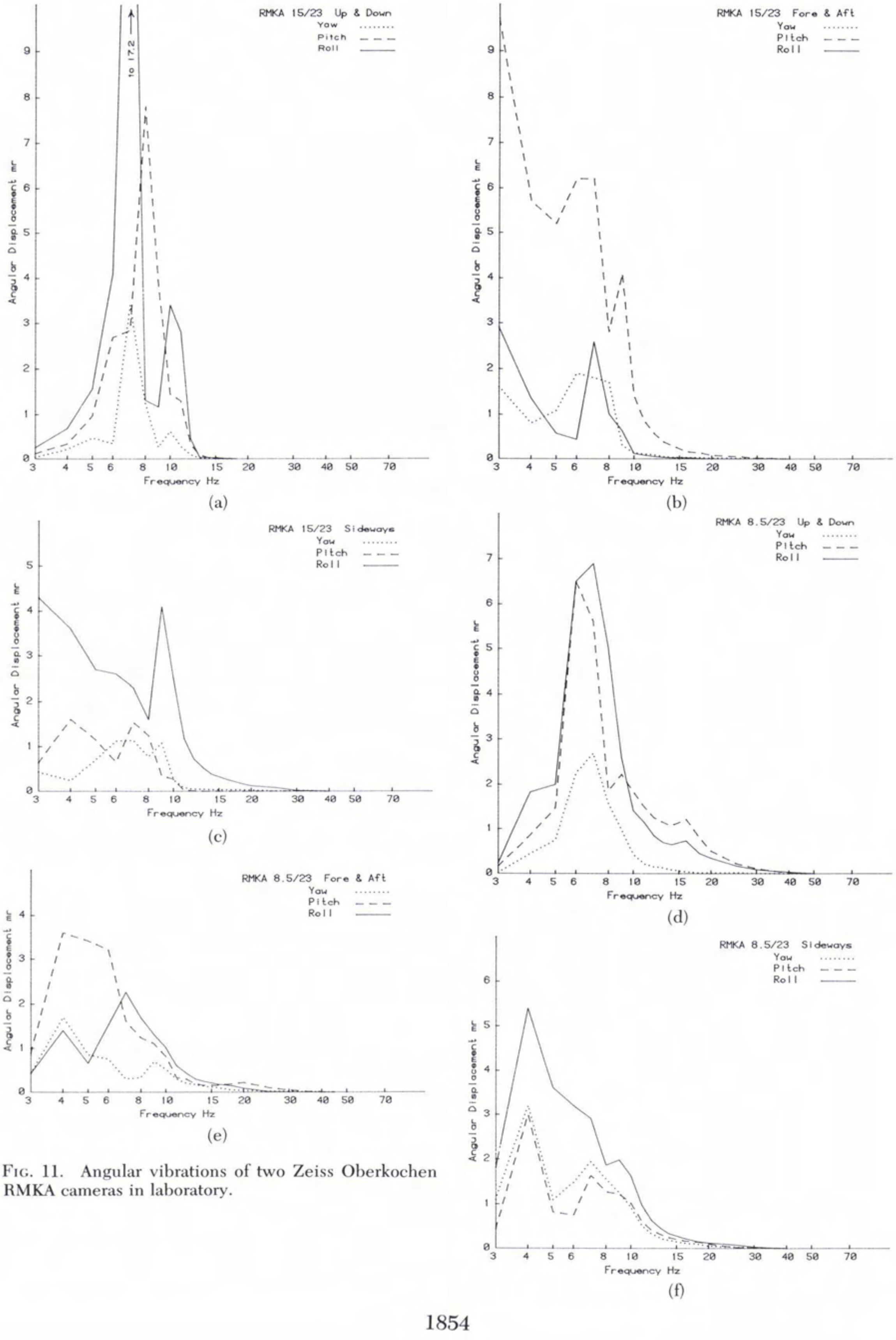
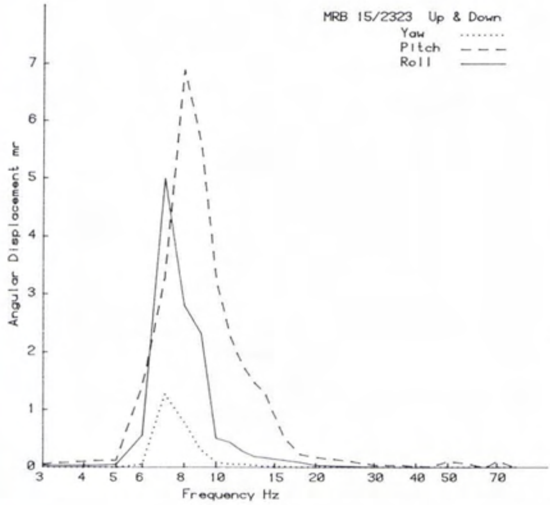
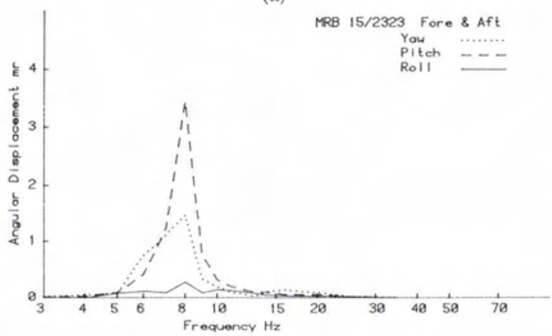


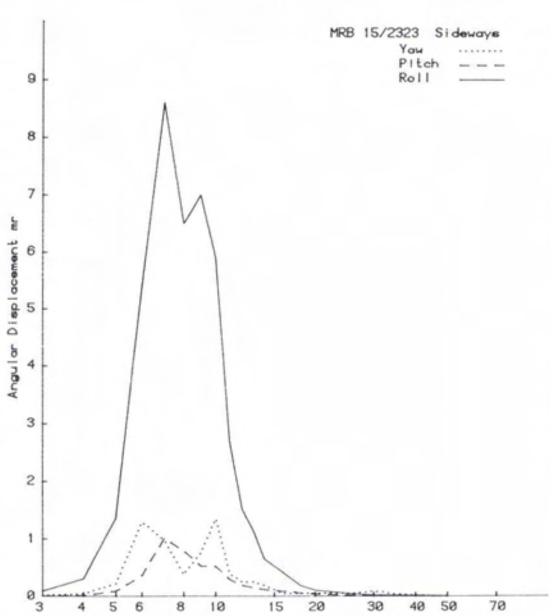
FIG. 11. Angular vibrations of two Zeiss Oberkochen RMKA cameras in laboratory.



(a)



(b)



(c)

FIG. 12. Angular vibrations of Zeiss Jena MRB camera in laboratory.

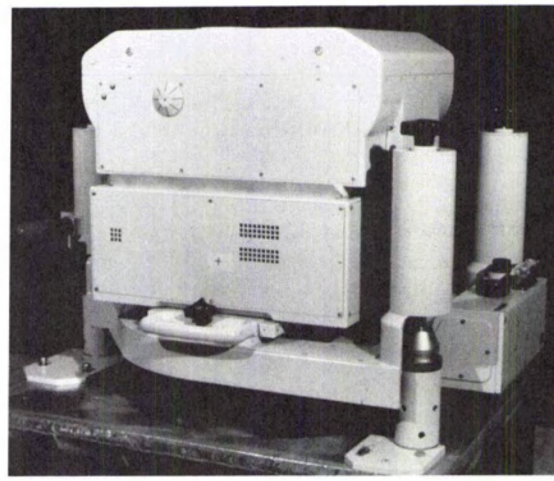


FIG. 13. The Zeiss Jena MRB camera. Anti-vibration mounts are up inside the three cylindrical posts.

be no more than 0.075 mr. If cameras with compensation for image motion due to forward motion of the aircraft become available, even better isolation from vibration will be desirable.

The desirable anti-vibration properties of a camera mount were stated by Brock (1952) and have been restated, along with discussions of the dynamic principles involved, by several of the authors referenced here. There are three goals: (1) To hold the camera and isolate it from vibration enough to prevent damage, (2) to avoid the conversion of linear aircraft vibration to angular camera vibration, and (3) to avoid the transmission of angular vibration from the aircraft to the camera.

The first seems to present no difficulties.

The second and third can best be met by a mount which supports the camera at (or near) its center of gravity and which is soft (low natural frequency) and well damped in torsional (rotational) vibration about its three axes. Reasonably good (soft and well damped) isolation from linear vibration is obviously helpful.

Center-of-gravity mountings do have some problems to challenge the designer. A rotationally free support such as a ball joint cannot be placed the center of gravity of a survey camera because the center of gravity is in the middle of the optical path. Thus, it becomes necessary to simulate support at the center of gravity by some mechanical arrangement. For example the axes of a gimbal system can intersect there (Brock, 1952, pp. 155–156; Carman, 1951b). Possibly, the camera could be supported on small portions of a sphere centered at the center of gravity. The center of gravity of the camera changes position with film load and as the film is wound. Compensation for this is desirable.

A soft mount may behave badly under conditions of excessive disturbance such as rough air, landing, or camera buffeting by airflow. Buffeting is avoided by use of a camera port glass. Rough conditions can be accommodated by stepped or graded spring rates, adding stiffness and damping as the camera departs further from its normal position.

Solution of these problems may have appeared too complex in 1950. Technological progress since then in such things as air bearings, variable rate springs and shock absorbers, electro-magnetic support and damping, sensors, and computer control should facilitate development of practical solutions.

Lens designs, camera mechanisms, sights, intervalometers, and controls have all undergone many improvements in recent years. Mount performance should not remain at the 1950 level but should move forward with the same vigor.

ACKNOWLEDGMENTS

The following organizations made this study possible by donating flying time: Capital Air Surveys Ltd., Department of Energy Mines and Resources, Department of National Defense, Lockwood Survey Corp., Photographic Surveys Inc., Spartan Air Services Ltd., and Survair Ltd. Optical, electronic, and mechanical arrangements for the flashing lights were fabricated by the Optical Components Laboratory, the Electronics Laboratory, and the Machine Shop of the Physics Division of N.R.C. Laboratory studies of vibration characteristics were carried out on the facilities of the David Florida Laboratory of the Communications Research Center under the supervision of B.W. Kinney. N.R.C. personnel involved in the operations and data analysis were G. Aubertin, H. Brown, A. Cameron, T. Draper, J. A. Hehir, K. J. McKee, J. E. W. Plummer, I. Powell, and A. Way-Nee.

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(Received 20 November 1981; accepted 1 March 1982, revised 30 March 1982)

APPENDIX A

Various workers have recommended limits on image motion ranging from 10 to 20 μm for the common aerial survey cameras and films. The 15-μm value used here can be considered as a middle value among these. It can also be considered as being based on the (Canadian) Interdepartmental Committee on Air Surveys' Specification for Aerial Survey Photography which requires that image motion not exceed 1/3 of the average lens-film resolved distance. The middle curve of Figure 1 has a weighted mean of 23 mm^{-1}. Thus, the resolved distance is 1/23 mm or 44 μm. One third of this is 15 μm. It should be noted that the tolerance for image motion becomes more strict as the inherent resolution of the lens-film system improves.