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HIGH SPEED RECORDING BY RESONATING OPTICAL RESOLVERS

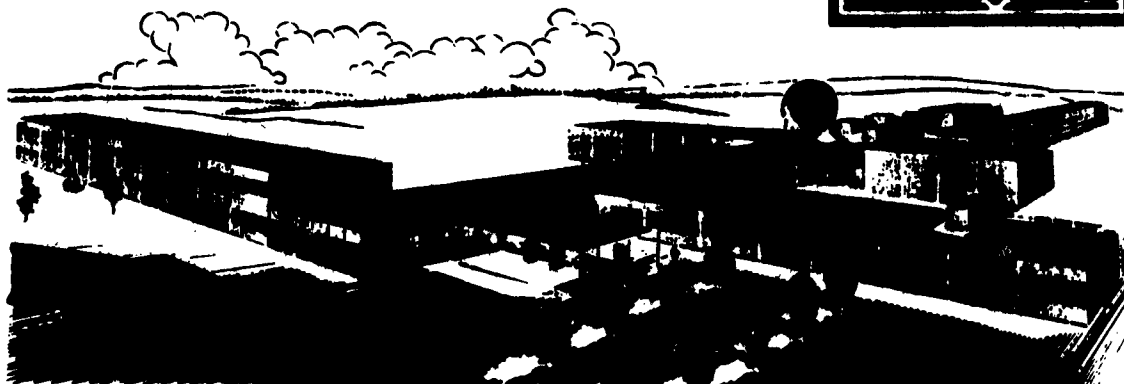
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DECEMBER 1961

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**AERONAUTICAL RESEARCH LABORATORY
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO**

FOREWORD

This interim technical report was prepared by the University of Dayton Research Institute, Dayton, Ohio for the Aeronautical Research Laboratory, Office of Aerospace Research on Contract AF 33(616)-6766 for the study of existing methods of achieving ultrashort-time exposures and a new method of utilizing oscillating optical elements. The monitoring laboratory was the Plasma Physics Research Branch, ARL with Dr. Wolfgang Braun as the contract officer. The work reported herein was accomplished on Task 70712, "Plasma Generation and Control" of Project 7073, "Research on Particle Dynamics".

The new method of achieving ultrashort-time exposures was conceived by Dr. W. Rambauske and Mr. R. H. Keith of the University of Dayton Research Institute. The principal investigator for the work performed was Dr. Rambauske who was assisted by Mr. Keith.

ABSTRACT

The application and design of resonant elements for high-speed spectrographic and camera work seems to be a unique new approach to specific tasks of the analytical physicist, and should provide a useful experimental instrument for the laboratory on earth and in space. Inexpensive construction and ease of operation characterize the new device, which has a time-resolution capability similar to the customary high-speed helium turbine drives with little or none of their operating difficulties. The findings of this preliminary investigation indicate that further study of the properties and applicability of oscillating drives should be of benefit.

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SECTION I

INTRODUCTION

Optically radiating physical events which either are of ultrashort duration (1μ sec and less) or are changing in ultrashort time intervals can be investigated by recording their images or the photometric values or spectra of their radiation taken in successive ultrashort time intervals. Since spectra permit an analysis of the molecular and atomic changes in the event, information gathered by time-resolved spectroscopy is far superior to other methods. Perfected procedures to obtain such spectra are desired: the highest possible time resolution should be combined with ultimate wavelength resolution, sharp definition, and exact fidelity of recorded intensities with respect to the emitted values. Time resolution can be achieved either by relative motion between the recording medium and the emitted light rays, when the changes of the event should be studied; or by interruption of the light rays, when only a single instant is of interest.^{(1)*} For the first method, photographic or photoelectric recording is usual, whereby the relative motion is accomplished by rotating drums or mirrors or by the deflection of an electron beam in an oscilloscope; for the latter method, the high-speed shutter is employed. Since all these procedures have certain limitations, another method has been conceived and investigated which by-passes many of these performance limitations, and exhibits many advantages which are described in the following description and calculations. This method makes use of vibrating piezoelectric crystals and may be called "High Speed Recording by Resonating Optical Resolvers." Although crystal-driven deflecting devices are described in several fields of scientific instrumentation,^(2, 3, 4, 5, 6) the application and design of vibrators for high-speed spectrographic and camera work seems to be a unique new approach to specific tasks of the analytical physicist, providing an experimental instrument with special advantages for the laboratory on earth and in space.

SECTION II

DISCUSSION

A. High Speed Spectrography

1. Methods of Obtaining Time Resolutions

Since the chief interest in the study of ultrashort light-emitting phenomena centers on the analysis of their spectra, the following exposition will deal with spectrographic devices. High-speed imaging cameras pose somewhat different optical problems and will not be considered in this report. There are two distinct ways of recording spectral events: either the emitted radiation is dispersed spatially into wavelength intervals, or one or several wavelength intervals are selectively filtered from the radiation. The time change is recorded either by deflecting

* Superscripts denote references.

the spectrum relative to a photographic film or by recording the intensity change of the selected radiation with a photoelectric receiver. As the spectrum is usually quite complex and has an unpredictable wavelength composition, the spatial dispersion of the spectrum will remain the primary and most reliable method, while the filter method will continue to be employed in special situations where the inherently high sensitivity of the photoelectric pickup is of greater importance. Of course, the given distinctions are not rigid; hybrid systems using photoelectric pickups for wider spectral regions as well as relative deflection systems for a filtered beam have been built.

Considering that an interpretation of a spectrum in terms of its atomistic origin can be properly performed only when line profiles, multiplets, range of series limits, and relative and absolute intensities are investigated, the display of wide spectral regions containing such multiplets will be necessary. If the experiment with the event can be repeated, a detailed study of a single selected line should accompany this analysis. Figure 1 illustrates the operating principle of an incident time-resolving spectrograph with photographic recording. Consider the real image P at the entrance plane of the instrument to be composed of light having wavelengths λ_1 , λ_2 , λ_3 and λ_4 . The spectrograph re-images P at the film plane as corresponding monochromatic real images along the horizontal axis: P_1 , P_2 , P_3 and P_4 . In order to obtain high wavelength resolution, the widths Δl of P should be small, so that P_1 , P_2 , etc. are narrow. If the spot P is moved vertically to a new position, t_1 or t_2 , the monochromatic images (the point spectrum) at the film plane is displaced to the corresponding heights t_1 or t_2 . In the conventional slit spectrograph a continuous vertical line of points from t_1 to t_2 at the entrance plane is illuminated simultaneously, producing corresponding lines at the film plane. In the incident time-resolving spectrograph only the single point P is illuminated, and is moved from t_1 to t_2 , producing corresponding motion in the film plane. Thus, the film record will display a spectral history of the image P , having wavelength resolution along the horizontal axis and time resolution along the vertical axis. The speed of relative motion between the images $P_1 \dots P_4$ and the film, and the vertical dimension Δt of the image P , affect the time resolution of the instrument. After the film area has been illuminated once from t_1 to t_2 by the relative motion of the spectrum λ_1 to λ_4 and the film, no further illumination should be permitted since it would overlap the first record.

The dispersion of wide spectral regions is produced by prisms or gratings, and interferometers combined with spectrographs are sometimes used to attain the ultimate in wavelength resolution.^(7,8) When the time-resolved record is made on film, either the film is moved against the dispersed spectrum, as in the drum spectrograph, or the spectrum is moved against the film, as in the rotating mirror spectrograph. The drum speed is limited by strong centrifugal forces at its circumference, and the width of the spectral region is limited to the narrow rim of the drum and to the small film width which can be properly employed. Since the ray path in the camera of the drum spectrograph must be deflected through a right angle in the short distance from the center to the rim of the drum, serious aberration problems arise which cannot be solved satisfactorily. Similar conditions hold for the rotating mirror spectrograph as long as one tries to incorporate the mirror

in the camera part of the spectrograph, since the reflecting surface of the mirror does not coincide with its axis of rotation and all aberrations become functions of the angular mirror position. The stigmatic and chromatic aberration problems cannot be solved for wide spectral regions with equal accuracy in an ordinary stationary spectrograph and this task becomes even more difficult when rotating elements are built into the instrument. Hence, it is advisable to use conventional spectrographs for high-speed time resolution and to produce the time resolution exterior to the dispersing instrument.

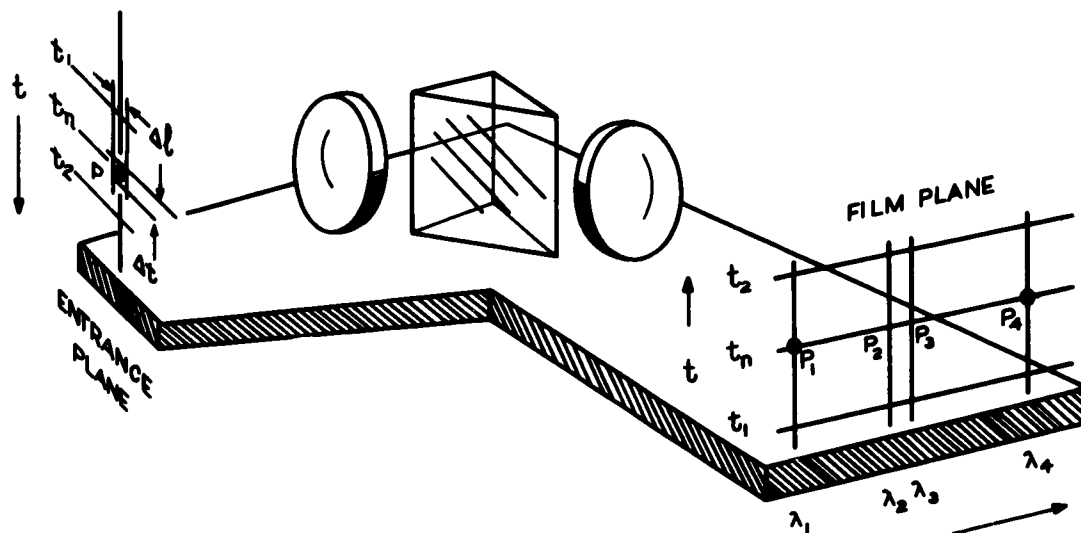


Figure 1. Schematic Representation of Incident Time-Resolving Spectrograph

This can be accomplished either on the incident (slit) or emergent (recording) side, the latter being advantageous only when photoelectric pickups are used. A photoelectric pickup employs several closely-spaced photomultipliers or an extended-photocathode image converter. The size of the multipliers limits the closeness with which their entrance slits may be spaced; hence a maximum-dispersion spectrograph is necessary for the successful employment of this method. The application of future fiber-optics developments may improve the performance of these systems. The electron-optical image-converter tube is not sufficiently developed to be suitable for spectrographic work. Geometrical aberrations and low resolution are typical. Designs which minimize these properties, such as the Lallemand tube, have no provision for resolving short time intervals, and must integrate the optical input during a relatively long exposure.

In conclusion, the most suitable method of producing high-speed spectrographic records is the production of time-resolution incident to an ordinary spectrograph. This can be accomplished only by a beam-deflecting device between the event and the entrance side to the spectrograph. According to the operating principle (Figure 1), the beam has to be imaged as a small spot upon the entrance slit of the spectrograph. The width Δl of the effective spot is limited by the width of the slit, which should be small enough to obtain the highest possible wavelength resolution. The height Δt and the speed of the spot along the slit determine the achievable time resolution.

2. Optical Considerations

A spectrographic system is described mainly by a) its dispersion (Angstroms per mm), b) its photographic resolution (lines per mm), c) its spectral range ($\lambda_b - \lambda_r$), and d) its speed (aperture ratio). Every given system requires different optical considerations for its proper illumination to utilize its qualities fully. If one improves one of these qualities, one usually has to sacrifice another. In high speed spectroscopy an additional final limitation is set by the steradiancy of the source (radiant power of source per unit area per unit solid angle). The illumination of the film in the time interval to be resolved must be sufficient for film blackening. The blackening depends on the film sensitivity, the H and D curve, the spectral characteristic curve, the reciprocity response, and the developing process for the film. In general, one can assume that about 0.2 erg cm^{-2} are necessary at 4500 Angstroms to produce unit photographic density of a blue-sensitive plate or film (0.15 erg cm^{-2} at 3500 Angstroms and 60 erg cm^{-2} at 5500 Angstroms).⁽⁹⁾ For a time resolution of 10^{-7} sec the illumination (irradiation) at the film should be at least in the order of 0.1 watt cm^{-2} or $0.01 \text{ watt mm}^{-2}$.

The total radiant power which is available at the film is determined by 1) the steradiancy of the source, 2) the source area, which illuminates the effective spectrum area, 3) the solid angle from the source to the film which can pass all effective stops, and 4) the transmission factor for all optics from source to film. As in the case of the four qualities of a spectrographic system mentioned above, all four factors cannot be improved independently, and therefore every individual case requires a different design which is best attained by practical experience.

In high-speed spectroscopy the linear resolution perpendicular to the dispersion, which is equivalent to the time resolution Δt , will not be much better than $1/2 \text{ mm}$. This permits from 20 to about 50 bits of time-resolved information from one exposure in the t -direction, since in this direction the exposed film area may extend from 1 cm to about 1 inch . Assuming that a spectral region 500 Angstroms wide will be spread over 100 mm in the direction of dispersion for an average dispersion of 5 Angstroms per mm, the area covered by the spectrum is $1/2 \times 100 = 50 \text{ mm}^2$ for a time element of 10^{-7} sec . This means that an average radiant power of 0.05 watts within a range of 500 Angstroms is required. Since the luminous and the radiant power are related by the well-known expression for the luminous efficiency,

$$\eta = 685 \frac{\int_0^\infty V_\lambda P_\lambda d\lambda}{\int_0^\infty P_\lambda d\lambda}, \quad (1)$$

where P_λ is the radiant flux per unit wavelength and V_λ is the relative luminosity at that wavelength, a conversion to photometric units cannot be performed as long as the character of the source is unknown. Hence the radiant power can only be estimated. At least 0.1 watt should be available in the total flux to produce the necessary 0.05 watts within 500 Angstroms.

A grating spectrograph with unit magnification may have a transmission factor of 60 percent, which indicates a necessary illumination of the slit with about 0.16 watt. Only light entering the slit is utilized; the effective slit aperture might be on the order of 20 microns wide and 1/2 mm high or $1/2 \times 1/50 = 1/100 \text{ mm}^2$, and the flux of 0.16 watts has to pass this small aperture. If this value is to be calculated for a specific case with better accuracy, it should be done according to the relation

$$P_{\Delta\lambda} = b R_{\Delta\lambda} K A \frac{d\theta}{d\lambda} \Delta\lambda \quad (2)$$

where $P_{\Delta\lambda}$ is the transmitted radiant power from slit to film, b the transmission factor, $R_{\Delta\lambda}$ the steradiancy of the source image on the slit, A the area of the collimator, K the allowable slit length per unit collimator focal length, and $\frac{d\theta}{d\lambda}$ the angular dispersion, all for the wavelength range $\Delta\lambda$.

Since in high-speed spectroscopy the slit is not simultaneously illuminated over its full length as in the case of stationary spectroscopy and since not all rays will pass the slit, the source image on the slit should transmit at least 0.2 watts through $1/100 \text{ mm}^2$. It is the task of an ideal optical system in front of the slit, which consists mainly of the transducer and the condenser, to supply this energy to the source image on the slit and to limit the size of this image to the $1/100 \text{ mm}^2$ area for every position of the image on the slit and without aberrations.

The illumination (irradiance) E of an image, which is the flux dF from a source of intensity I into solid angle ω reaching an area dA of the image, is given by

$$E = \frac{I \cos \phi}{r^2} = \frac{dF}{dA} = \frac{I d\omega}{dA} \quad (3)$$

The flux passing an optical system with an entrance pupil which subtends the angle 2θ at the source is

$$F = \pi B da \sin^2 \theta \quad (4)$$

with "da" as source area and B as the emittance per unit area of the source.

The entrance pupil for the optical transducer system is the image of the effective aperture stop formed by the condenser. The angle θ can be varied to an optimum by proper choice of the condenser aperture ratio, the distance of the deflecting element from the condenser, and the size of this element. (This element is usually a mirror and will be made the effective aperture stop.) A numerical variation of these parameters for a fixed value of the element size gives the optimum angle θ .

However, since the image area is predetermined as was explained above, and since the angle of acceptance at the slit should be equal to that given by the aperture ratio of the spectrograph, another variation problem has to be calculated.

A small image area could best be achieved by negative magnification of the system, because the illuminance varies inversely with the square of the magnification. A negative magnification means a smaller image distance than object distance, a requirement which is in opposition to a larger distance between deflecting element and slit for maximum time resolution. If this distance is determined, for example, to be 1 meter, the insertion of a cylindrical lens parallel to the slit will be helpful, since the concentration of rays must be about 50 times higher in the direction perpendicular to the slit than in the scanning direction; for the slit width is only about 20 microns, while the height of the beam spot at the slit Δt might be 1 mm (1000 microns) corresponding to 1/2-mm height resolvable at the film.

Assuming the large value of 25° for angle θ , $\sin \theta$ becomes 0.43 and $\sin^2 \theta$ is 0.176. The quantity $\pi \sin^2 \theta$ becomes 0.55; hence about half of the measured emittance of the source into the half-sphere around the source would enter the optical system. The negative magnification at maximum might be 2 in the scanning direction and 50 in the direction perpendicular to the slit, which permits an emitting source area of 2000×1000 microns, an area of 2 mm^2 for "da." Hence these 2 mm^2 have to emit 2×0.2 watt which corresponds to 0.4 watt, or 20 watt per cm^2 . However, the system also has a transmission factor, decreasing with the number of optical elements, which will not be better than 30 percent. Therefore, with an optimum optical system the source should at least emit about 70 watt/ cm^2 integrated over the spectrum. An increase of the effectiveness of the optical system can be accomplished by enlarging all parameters in scale; nevertheless, the size of the deflecting element soon reaches a final limit given by mechanical considerations explained in Section II-B-3. In this respect rotating and oscillating systems are very similar. However, the small deviations of the scanning beam in an oscillating system permit much more freedom for the designer to combine the properly chosen parameters for the optimum performance of the system.

3. Problems Attendant to Spectrographic Methods in Use

Aside from the available light intensity and the choice of the proper method or instrumental design, other factors determine the usefulness and value of a high-speed spectroscopic system. Problem areas are: sensitivity, fidelity, timing, and triggering. 1) It is obvious that the sensitivity of the recording medium, whether film or photoelectric surface, limits the time resolution and wavelength resolution which can be obtained with an event of given specific brightness (luminous power). Another important factor is the actual illuminance at the medium, which depends on the amount of radiation captured by and attenuated within the transmitting optics. For example, when Kerr-cells are used as shutters, at least 80 percent of the light will be absorbed.⁽¹⁰⁾ 2) The radiation passes through various optical elements to the final record. The spectral characteristics of the radiation, i.e., intensities versus infinitesimal wavelength intervals, might have altered during this propagation. The recording medium may also exhibit altered selective spectral sensitivity when illuminated only for an ultrashort instant. These variations therefore might be functions of brightness,

wavelengths, and duration of light pulse or pulse action of the recorder. Moreover, an influence of the state of polarization may be present. Although the general reciprocity of photographic emulsions has been thoroughly investigated,⁽¹¹⁾ not so much is known about their spectral reciprocity deviations. The response of photoelectric devices, especially in the millimicrosecond region, is even less known. Kerr-cells, although widely employed as shutters in high-speed imaging photography, are unsuitable for high-speed spectroscopy, because their selective attenuation is an uncertain function of shutter time, voltage and other parameters. Their transmission is limited to small wavelength bands; the nitrobenzene-filled cell transmits energy only within the central portion of the visible spectrum.⁽¹⁰⁾ When Kerr-cells are eliminated as shutters, the problem of timing becomes serious in high-speed spectroscopy. 3) In any case where the duration of emission from the event is longer than the time-capacity of the record, an overlapping of exposure on the film or oscillogram will occur which obscures the information of interest. The same holds true when the event or its surroundings emit radiation before the desired information is recorded. The explosive shutter is inconvenient,⁽¹²⁾ but it is the only device known to be in common use for shutting off recorder illuminations with the desired speed. It produces fumes which introduce a second spectrogram into the record; it is not fully reliable, exhibits a large variation in exposure time, and its additional attenuation always reduces the intensity of the light rays. No completely satisfactory method has been found for opening a shutter at a given instant aside from the common technique of triggering the event at a predetermined point of the beam-deflection cycle. 4) Four principal triggering possibilities exist: the high-speed transducer triggers the event; or the event triggers the transducer; or both are triggered at will through corresponding delay lines from the outside; or both the event and transducer are completely independent from each other. Obviously the last design is most desirable, since it would be capable of performing all the functions of the other methods, and would have additional unique applications.

Summarizing the factors stated in Sections II-A-2 and II-A-3, a high-speed spectrographic arrangement should have: an ordinary spectrograph for a wide spectral region as the dispersing instrument, exterior beam deflection at the incident side of this spectrograph by a time resolver, precise shutter action avoiding elements which attenuate or alter the spectrum, independence of event time and beam-deflector position with respect to triggering, a photographic record for a wide spectral region, and a photoelectric record for single spectral lines accompanying the photographic record.

B. Time Resolvers

1. Resonating Optical Time Resolver

The exterior beam deflection can be accomplished in the present state of optics only by an angular or longitudinal displacement of a reflecting or refracting element. This may be done either by a rotating mirror or by a periodically oscillating mirror as in the case of the resonating optical time resolver. Both

procedures pose essentially the same optical problems and both are ultimately limited in speed by the same mechanical property: the tensile strength of the material of the deflecting element. However, the procedures have distinct technical properties which modify their ease and aptness of applicability and result in the superiority of the oscillatory method. The Resonating Time Resolver is an electromechanical transducer. The frequency of operation can be accurately set to a predetermined value or synchronized with some other device. It may even be driven by the amplified output of a primary frequency standard. The optical beam deflector might be a plane reflecting mirror. The angular vibrating motion of the surface is produced by the vibrations of a piezoelectrical crystal which is driven by amplified signals from a frequency generator. The piezoelectric vibrations are of small amplitude and high frequency; their form is not linear but sinusoidal. However, the deflected beam should have linear rather than simple harmonic motion in scanning the slit of the spectrograph, and this has been accomplished by combining out-of-phase simple harmonic deflections from two vibrating crystals into a circular deflection, in the manner of the composition of the familiar Lissajou figures. The beam speed along its circular path is then constant; the circle has a second advantage that its radius can be controlled by change of the voltage to the crystals. If this change is performed by a pulse shorter than four or five vibrational periods, the circle will scan the slit only within one period, and the third problem, timing, mentioned in Section II-A-3, is solved. No overlapping and rewriting will occur and any shutter system is avoided. The light emitted from the event does not suffer attenuation and spectral changes as in a Kerr-cell or an explosive shutter; and sensitivity, fidelity, and timing are brought to their optimum (Section II-A-3). The fourth problem of triggering might also be solved by this method.

Since the maximum attainable piezoelectric amplitudes are inversely proportional to the frequencies employed and the writing speed is determined by the product of amplitude and frequency, the optimum values for these basic parameters have to be determined. These optimum values depend on numerous other physical conditions. The achievable maximum, however, is basically defined by the ability of the mirror material to follow the vibrational accelerations which is in turn defined by the ability of the mirror material to follow the vibrational accelerations which is in turn defined by its mechanical properties, just as in the case of the rotating mirror where centrifugal forces set the ultimate speed limit. Section II-B-2 gives a numerical estimate of this limit. Nevertheless, more experimental research is necessary to answer these questions unambiguously. In the feasibility model of the method described in Section II-B-3, the deflecting mirrors are directly fixed to crystals vibrating in torsional motion. However, a longitudinal motion and a higher resonance frequency may be preferable; the crystal motion would be transmitted to the reflecting surface by a metallic transducer of exponential shape, with two crystals acting on the same mirror surface in push-pull operation.

Because the oscillatory system is compact, very easily synchronized, simple, and even extraordinarily inexpensive, it is practical to use several resolvers in series, with a multiplication of the emergent deflection angle of the writing beam. An advantage of the use of the vibrating method of beam deflection with small amplitudes in series is that the mirror size does not grow exceedingly

large as in corresponding rotating devices, since the inter-mirror distance can be kept very small. In Section II-A-2 it was estimated that a time resolution of 10^{-7} sec in a spectrograph of unit magnification with a dispersion of 5 Å/mm can be achieved only when the emission of the source in the visible spectral region is in the order of 70 watts/cm². Ordinary plasma phenomena, the time resolution of their spectra now desired for research purposes, will not exceed this value substantially. Hence writing speeds of 5×10^5 cm/sec up to 5×10^6 cm/sec would be sufficient to obtain spectra with good wavelength resolution for sources of a luminosity between 1/100 to 1/10 of the sun (surface emission of the sun is 6.2×10^3 watts/cm²).

In Section II-B-2 of this report, it is shown that a one-inch mirror is restricted to vibrational speeds having a peak rotational velocity of 4×10^4 rpm or less by stresses in the driving horns. For a single resolver operating over a one-meter distance, this corresponds to a theoretical peak writing speed of:

$670 \text{ rev/sec} \times 2 \text{ rev sweep/rev mirror} \times 200 \pi \text{ cm/rev sweep} = 8.4 \times 10^5 \text{ cm/sec}$,
or a value in excess of 10^6 cm/sec through the use of two ideal resolvers in series.

Other stress limitations peculiar to an individual resolver design or a requirement for ultimate reliability through operation at large safety factors may prevent operation at this peak speed. However, the simple twister "bimorph" crystal employed in the experimental work (see Section II-B-3) produces simple-harmonic-motion deflections of 3.3 cm at 3450 cps over a one-meter lever arm in response to an input of 250 vrms. This corresponds to a peak writing speed of:

$3.3 \text{ cm def} \times \pi \text{ cm peak/cm def.} \times 3.4 \times 10^3 \text{ cps} = 3.5 \times 10^4 \text{ cm/sec}$;

thus three resolvers of this rudimentary type will produce deflections in excess of 10^5 cm/sec. It is to be emphasized that this is the maximum number of resolvers that would be required for a 10^5 cm/sec device, and represents the use of easily-available crystals of minimum cost, without horns or other transformers to increase the velocity obtained from the crystal itself, and operation at a proven, ultra-conservative level which has permitted extensive experimental use without a single failure or impairment of the transducer action. More efficient use of crystal capabilities through the employment of mechanical transformers and better crystal-load matching, or through the allowance of more strenuous crystal action, can be expected to decrease the number of series resolvers required.

Prism spectrographs can be superior to grating spectrographs with respect to sensitivity (photographic speed), but they are inferior with respect to linear resolving power. When prism systems are used, optically simple designs are possible if the natural line curvature is compensated by a curved slit. The circular scanning of the beam emergent from the ultrasonic time resolver can be made coincident with the slit curvature. In grating spectrographs for short time resolutions only, a stigmatic design should be employed, since only a small portion of the slit is illuminated at a time and only a small extension of the corresponding image in the slit direction is desired. The different means to reduce astigmatism

can be combined with slit curvature to simplify the design of the optical elements in the spectrograph. A slight curvature, therefore, in the scanning path is advantageous, if the transducer and the spectrograph are considered to be a single unit by the designer.

2. The Rotating Mirror

The Rotating Mirror might be either of the double-face or the multi-face type. The multi-face mirror exhibits more difficult optical problems, since the reflecting surfaces are displaced a larger distance from the axis of rotation and therefore have a significant longitudinal motion component with respect to the light rays. On the other hand, more conventional rotational speeds may be effectively utilized, and electric motor drives are practical. Nevertheless, flutter, vibrations, and surface bending by centrifugal forces limit the time-resolutions achieved with multi-face mirror wheels. The double-face mirror can be driven to high speeds with accompanying centrifugal forces approaching the yield strength of the mirror material. Since these centrifugal forces are a function of the mirror size, the mirror size is the second limiting parameter. The gas turbine is found to be the only suitable driving means, since it exhibits burst limitations of lesser magnitude than the mirror itself. Mach-limited turbine and mirror tip velocities determine its top speed. The smaller the molecular weight of the gas, the higher the turbine speed which can be reached. Helium has a high sonic velocity and is usually employed at pressures in excess of 100 psi. One million rotations per minute have been achieved. The technical features of double-face mirrors and mirror wheel devices (13, 14, 15, 16, 17, 18, 19) are described in the literature.

Although the rotational speed of the double-face mirror is sufficient for solving almost all spectrographic time resolution problems because of the usually limited brightness of the event, special attention should be directed to many technological and optical disadvantages of this system. First, in many applications the rotating mirror system needs a light-attenuating and spectral-character-altering shutter; second, the mirror surface and the axis of rotation cannot be made to coincide, enhancing optical aberration problems; third, the turbine exhaust engulfs the mirror, preventing vacuum use and introducing ambulant scattering; fourth, the high speed rotation exerts strong gyroscopic effects to the mechanical system, which hinder the use of the system in accelerated or turning vehicles, such as satellites, spacecraft, rolling ships and aircraft; fifth, oil drops and fumes cover the mirror and optics after short operation; sixth, the system is dangerous: the mirror operates near its bursting strength and at sonic tip velocity implying a significant shrapnel hazard; seventh, the costs of the system and its operation are very high: the supply of one bottle of helium with 189 ft³ volume at standard conditions lasts for only two to three minutes of operation time, which includes time for acceleration and deceleration; and eighth, the turbine rotational speed cannot be precisely monitored without the use of an ancillary tachometer and control system. The control must operate through throttling of the turbine gas input. Synchronization with frequency standards or the attainment of a preselected speed becomes increasingly difficult as greater precision is demanded. Considering these drawbacks of the rotating mirror, it is proper to look for a different system which

avoids them; this was found in the vibrational mirror driven by alternating voltages of a signal generator which discarded pneumatic-mechanics in favor of electronic and electro-mechanical operation.

3. Stress Limitations on the Speed of Rotating and Oscillating Resolvers

Fundamental limits of the maximum speeds attainable exist for moving resolvers. In contrast to other additional technological limits, such as those imposed by the capabilities of present-day bearings upon rotating machinery, or other stresses peculiar to specific design configurations, these fundamental limits are dictated solely by the size and shape of the resolvers and the mechanical properties of the resolver material of construction.

Rotational stresses in wheels of geometrically similar profile are identical at similar radial locations. For a given diameter the stresses are proportional to the square of the speed; for a given speed the stresses are proportional to the square of the diameter: in other words, geometrically similar disks will be equally stressed when running at the same peripheral velocity.

The stress distribution in a rotating disk, such as that used in multi-face rotating mirrors, is described under elastic conditions by two differential relationships, a force - equation 5, and a continuity - equation 6:

$$\frac{dS_r}{dr} = \frac{S_t}{r} - \frac{S_r}{r} - \frac{\omega^2 \delta}{g} r - \frac{S_r}{t} \frac{dt}{dr} \quad (5)$$

$$\frac{dS_t}{dr} - n \frac{dS_r}{dr} = (1+n) \left(\frac{S_r}{r} - \frac{S_t}{r} \right) - E \alpha \frac{dt}{dr} \quad (6)$$

where:

r = radius to point in question, in.

S_r = radial stress, psi

S_t = tangential stress, psi

ω = angular velocity, radians per second

δ = density of steel, 0.282 lb per cu in ($\omega^2 \delta / g = 8$ at 1000 rpm)

g = gravitational constant, 386.4 in per sec²

t = axial thickness, in.

T = temperature, °F

E = modulus of elasticity, 30,000,000 psi

n = Poisson's ratio, 0.3

α = coefficient of thermal expansion, 0.000006

For a disk of uniform thickness and temperature, the last terms of Equations (5) and (6) disappear. With an outer radius of r_2 inches at 1000 rpm, the maximum value of S_t occurs at the center

$$S_{t \text{ max}} = (3 + n) r_2^2 \quad (7)$$

as does the maximum value of S_r .

$$S_{r \text{ max}} = (3 + n) r_2^2 \quad (8)$$

The factor of safety against bursting is fairly well represented by comparing the strength of the material with the average tangential stress throughout the cross section of the wheel.⁽¹⁹⁾ At 1000 rpm the average bursting stress in a flat disk is

$$S_{t \text{ burst}} = \frac{8}{3} r_2^2 \quad (9)$$

For a thin two-faced rotating mirror, tangential stress is not present to a significant degree. The radial stress maximum is at the center:⁽²⁰⁾

$$S_{r \text{ max}} = \frac{1}{2} \omega^2 g r_2^2 / g \quad (10)$$

For a rotational speed of 1000 rpm this becomes:

$$S_{r \text{ max}} = 4 r_2^2 \quad (11)$$

Thick two-faced mirrors and mirrors having three or more faces are more difficult to analyze, since they do not closely approximate either of the thoroughly-developed cases presented above. However, data on the relative bursting speeds of these wheels has been given by Brixner.⁽¹²⁾

A thin mirror, set in oscillatory motion about an axis tangent to its face, will exhibit a maximum radial stress at its center equal to that given by Equation 6.6. This value will be highest when the angular velocity of the mirror is maximum: at the midpoint of its travel in the usual simple harmonic motion generated by most high-speed electromechanical transducers.

With a maximum unit strain of 5×10^{-4} possible for most synthetic crystals, the limiting particle velocity is about 65 inches per second,⁽²⁾ and hence crystals cannot be used successfully in the direct driving of a mirror resolver of high speed. If, however, a transducer is glued to a metal rod tapered exponentially like a horn, a very high terminal velocity at the small end can be produced. The taper is an exponential function of the length. If the total length of the steel piece is made an integral number of half-wave lengths of the transducer frequency, the glued joint will come at a loop of the motion and will not be appreciably strained. However, the strains within the horn place a limitation on the

motion of a horn-transducer combination that could be used to drive a mirror. The particle velocity of the steel section adjacent to the crystal is the same as that of the crystal surface. The strain in the metal coupling at the nodal point (maximum stress occurs at the node) is described by

$$\sigma_{h \max} = U/v_s \quad (12)$$

where $\sigma_{h \max}$ is the maximum strain encountered in the horn, v_s is the velocity of sonic propagation in the steel, and U is the particle velocity at the surface. The maximum stress developed in the horn is thus

$$S_{h \max} = U E/v_s \quad (13)$$

The effect of the tapering of the horn is to increase the particle velocity in inverse proportion to the diameter. Therefore, the strain at the nodal point is equal to

$$\sigma_{h \max} = \frac{d_o v_c \sigma_c}{d_1 v_s} \max \quad (14)$$

where d_o and d_1 are the large and small diameters of the horn, v_c is the velocity of propagation of the wave in steel, and $\sigma_c \max$ is the maximum strain encountered in the crystal. By use of this principle in constructing horns with a high d_o/d_1 ratio, unit strains in excess of 0.01 can be developed in steel without exceeding a value of 4×10^{-4} in the crystal. (2)

If, for example, such a horn coupling drives one edge of a flat mirror in simple harmonic motion perpendicular to the mirror surface, with the opposite edge fixed but free to rotate (corresponding to half of a mirror driven by two horns in push-pull operation), a peak angular acceleration of the mirror is produced which is given by:

$$\omega_{\text{peak}} = U/r_2 \quad (15)$$

where r_2 is the distance from the outer edge of the mirror to the pivot. Combining (15) with (13), it is seen that the maximum stress in the horn is related to the peak angular velocity of the mirror driven by it:

$$S_{h \max} = E \omega_{\text{peak}} r_2/v_s \quad (16)$$

For a peak rotational velocity equivalent to 1000 rpm and using the value of 30,000,000 psi for E and $v_s = 2.0 \times 10^5$ in/sec, Equation (16) becomes:

$$S_{h \max} = 5 \times 10^3 r_2 \quad (17)$$

which is directly proportional to velocity and mirror size, not to the square of these quantities as in the relationships given above for all other aspects of mirror motion.

The material showing the best characteristics for high-stress devices is Allegheny Ludlum 609 steel and is the customary material used in maximum-performance high-speed rotating mirrors. The 609 steel has an elastic limit of 240,000 psi, and maximum operating speeds are usually based on a tensile strength which is 75% of that value.⁽¹⁴⁾ Information is not available on the fatigue strength of this steel, but the usual assumption of 40% of the yield should be valid for the calculations involving oscillatory motion. Assuming moving mirror devices having the periphery one-half inch from the axis of rotation (a typical size for two-faced mirrors but a very small size for multifaced disks),^(13, 14) the maximum stresses at 1,000,000 rpm (16,700 rps) are:

8.25 x 10 ⁶ psi for a uniform rotating disk	From (Eq. 8)
2.5 x 10 ⁶ psi calculated burst average for a uniform disk	From (Eq. 9)
10 ⁶ psi for a thin rotating two-faced mirror	From (Eq. 10)
10 ⁶ psi for a thin vibrating mirror	From (Eq. 10)
2.5 x 10 ⁶ for the horn driving the oscillating mirror	From (Eq. 17)

However, at 1,000 rpm, the centrifugally-induced forces become negligible for these devices in contrast to the horn stresses which decrease directly rather than as the square of the speed as was mentioned earlier. In analogous fashion, the use of larger mirrors would not increase the horn stresses as much as the other loads. The equivalent values for these mirror devices at 1,000 rpm are: 8.25 psi, 0.25 psi, 1.0 psi, 1.0 psi, and 2.5 x 10³ psi.

Similarly, the maximum attainable speeds are found to have limits, set by the mirror or horn material and the mirror size, of: 1.5 x 10⁵ rpm, 8.5 x 10⁵ rpm, 4.2 x 10⁵ rpm, 3.1 x 10⁵ rpm, and 4.0 x 10⁴ rpm, respectively. Since both the vibrating and the rotating thin mirrors are subject to the same centrifugal loading limits under equivalent operating conditions, and since the rotating mirror may be loaded to a level permitted by a finite number of stress cycles while the vibrating mirror should be loaded to a lower level permitting an infinite number of stress cycles, the ultimate performance of a single vibrating mirror must always be penalized by the difference between the normal and fatigue strengths of the mirror material. However, this relative advantage is completely reversed if several of the inexpensive electromechanical resolvers are operated in series.

C. Experimental Work

The experimental investigation of high-speed optical recording utilizing oscillating resolvers has been directed towards four areas of interest. Each portion of the study was designed to test the feasibility of methods proposed and to disclose new methods of operation which might yield significant benefits. Transducer principles, designs, and performance have been studied with the purpose of selecting the most practical methods of driving optical elements. The optical considerations involved were investigated to obtain an insight into the problems of image formation peculiar to moving-mirror devices, as well as to disclose new and refined

methods of deflecting the beam so formed. Synchronization, triggering, and other ancillary areas of interest were brought under study, not only to insure reliable operation but also to widen the usefulness of recording devices by making them applicable to a greater scope of test situations. An investigation of other optical recording devices now in use also served several purposes: these devices have been used in the instrumentation of capability studies of vibrating-resolver systems and their operating principles have suggested alternate methods of producing time resolution with vibrating resolvers; in the course of using these cameras in this connection, several modifications were made which should enhance their inherent usefulness as recording devices.

1. Transducers

Medium-frequency resolvers were constructed by modification of Astatic X26 recording crystal cutters. These cartridges employ a twister bimorph crystal which imparts torsional motion along the axis of the needle chuck. A preliminary design utilized the suspension of the cutter as manufactured, the needle chuck set-screw being replaced by a threaded holder which positioned a 3 x 3 x 0.5 mm front-surface mirror with the axis of rotation coincident with the centerline of the silvered surface. This design was later refined to permit higher-amplitude operation: the sharpness and intensity of resonance was increased by removing the soft rubber bushings and clamp supports employed in damping the cartridge response in its original application. The needle chuck and clamp assembly was also discarded with a saving in moving mass and a corresponding increase of the natural frequency. A 9 x 9 x 0.5 mm front-surface mirror was cemented directly to the surface of the twister element, an aperture was bored in the case to permit optical access to the mirror, and the cartridge was reassembled. The transducer unit which results is reliable, provides protection for the piezoelectric element and mirror, is easily mounted, and can be constructed in an hour's time at a materials-and-parts cost well under ten dollars. Typical frequency response and output curves of modified X26 cartridges are shown in Figures 2 and 3. Crystal cutters modified to drive the larger-size mirrors were employed in the bulk of the experimental work described.

Two forms of "Capadyne" electromechanical elements manufactured by Mullenbach Electronics were also tested. These transducers consist of a layer of active ceramic material bonded to a thin plate of titanium which matches the thermal coefficient of expansion of the ceramic. These elements respond to DC as well as AC, and produce a bending motion in the same direction on the application of a charge of either polarity. Loads in excess of 20 grams can be borne by a single element, with little or no diminution of response; typical action is 10^{-3} inch for an applied potential of 250 volts. Cantilevered elements 2 x 0.5 x 0.02 inches in size were tested, and strong resonances at 20, 40, and 60 cps were observed. Several weak harmonics are present up to 3000 cps, but the amplitudes of motion observed seem insufficient for optical applications. Disk elements 2-1/2 inches in diameter were also investigated. A tympanic motion is obtained, and results were essentially the same as those observed with the cantilevers.

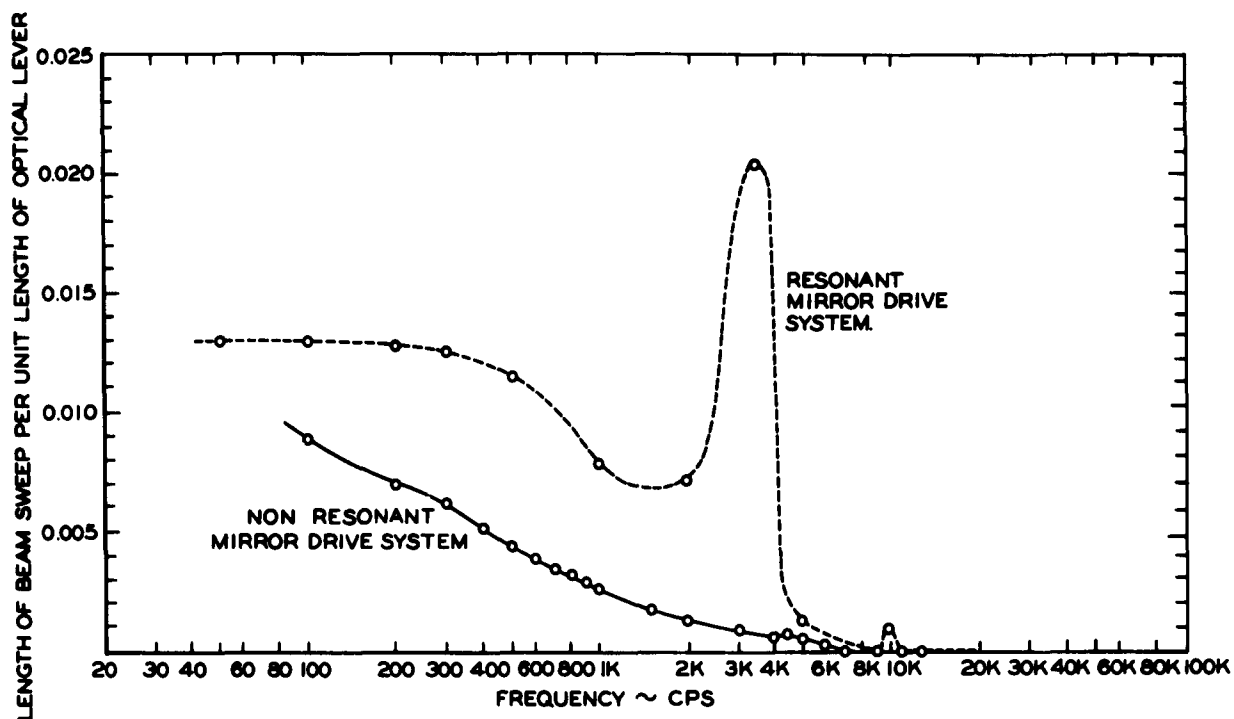


Figure 2. Frequency Response of Medium-Frequency Mirror-Drive Systems - Crystal Excitation: 150 V rms Sine Wave

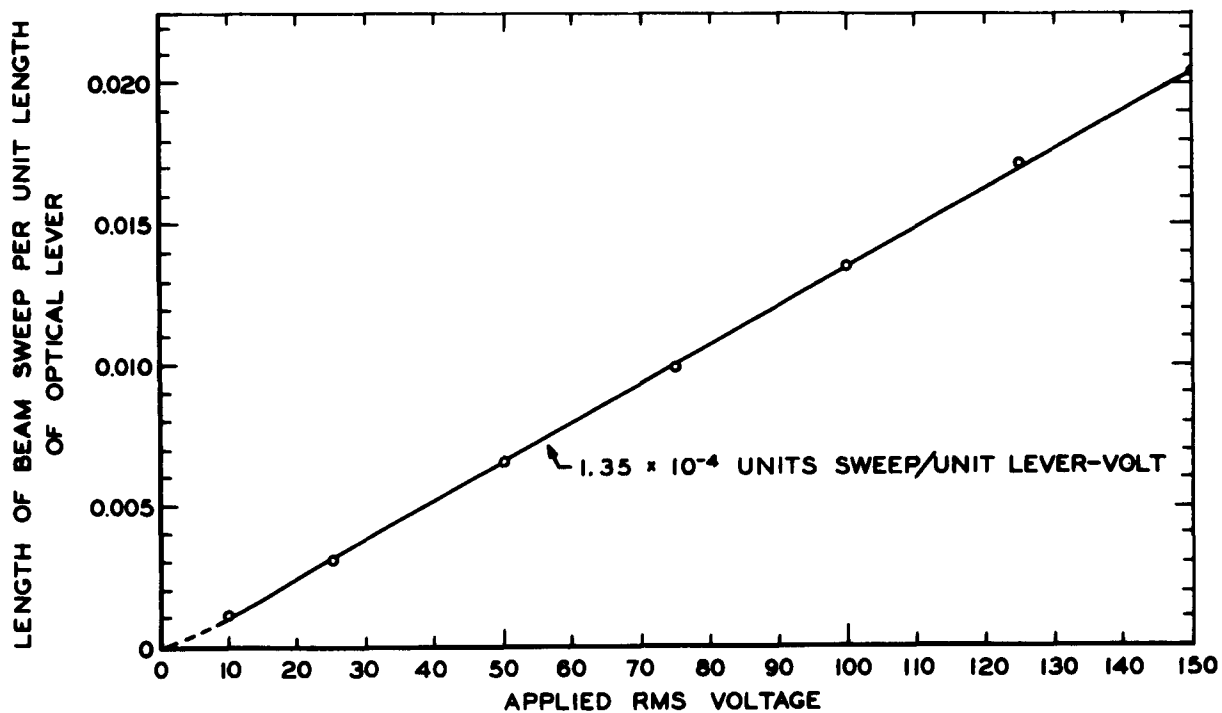


Figure 3. Beam Sweep for Sine-Wave Inputs at Various Voltages for Resonant Medium-Frequency Mirror Drive at Resonant Frequency of 3450 cps

Several tubular piezoelectric transducers have been studied; these devices are fabricated of "PZT-5," a proprietary polycrystalline material produced by Clevite Components Corporation. The material features a higher electromechanical coupling than any other piezoelectric ceramic material, has good properties at elevated temperatures, small aging effect, high resistivity and dielectric constant.⁽²²⁾ The transducers have been sized to be resonant in the 50 to 100 kc region in the length-expansion mode. The magnitude of motion has been observed using interference methods, and should be applicable to optical work.

Clevite has also been investigating the possibility of fabricating a tube from a single crystal of ammonium dihydrogen phosphate for our evaluation. A torsional motion about the axis of the cylinder is produced upon application of electrical excitation of the inner surface and two 90° segments of the exterior.⁽²⁾ The torsional ADP crystal has no commercial application at this time; thus custom cutting and electrode attachment will be required.

A Sheffield ultrasonic cutting tool has been obtained from the Electrical Engineering Department of the University of Dayton. Magnetostrictive action drives the cutting head in the longitudinal mode of vibration; operation is in the vicinity of 25 kc. This apparatus is intended to be used in connection with studies of mirror-transducer coupling methods as well as an evaluation of magnetostrictive drives.

2. Image Formation

The optical system originally used in the experimental work was rather simple: an incandescent projection bulb illuminated a pinhole through a condenser or a zirconium arc point source was used directly as the object, and an anastigmatic lens focused the rays into a cone which was reflected from two vibrating mirror resolvers, and came to a focus approximately two meters beyond the final mirror. Anastigmatic lenses of 102 mm, $f/2.7$, or 13 mm, $f/1.9$ were utilized.

Later work employed a system which is particularly suited to the small-stop conditions imposed by moving mirrors. A positive lens formed a cone of rays from the object; the cone was intercepted near the focus by a negative lens which relayed the image over the mirrors to the focal plane. This arrangement is similar to the familiar telephoto system and produces a narrow, almost-parallel bundle of light from the negative lens to the focus, yet retains a wide objective aperture and reasonable focal distances. Typical operation utilized a 75 mm $f/1.9$ oscilloscope camera lens (corrected for short working distances) 50 cm away from the object, a 30-mm diameter -26-mm focal length double-concave simple lens spaced 5 cm behind the objective and an optical path of 1.5 meters over the moving-mirror resolvers to the focal plane. Utilizing an object 2 x 2 mm in size, the beam produced has a maximum width of about 12 mm over the entire 1.5 meter throw.

3. Beam Deflection

The methods of beam deflection can be classified into two types: transient and continuous-wave. In either case, the beam is deflected across the recording

medium in a line, and is displaced perpendicular to its main direction of travel on its return, thus preventing rewriting and the resulting obfuscation of the original record.

Continuous-wave beam deflection is used in forming the familiar Lissajou patterns, in the simplest case by applying signals of the same frequency having a phase difference to two transducers operating to deflect the beam in mutually perpendicular directions. A sine wave of known frequency is obtained from an audio signal generator. The signal passes through $+45^\circ$ and -45° phase-shift networks, is amplified through a dual-channel system, and applied to the crystals. A schematic diagram of this arrangement is shown in Figure 4. Typical patterns produced in this manner are shown in Figure 5. If the oscillating mirrors are placed so that the displacements they produce are not mutually perpendicular, greater amounts of displacement in elliptical patterns may be obtained utilizing the same conditions for other variables. Typical results are shown in Figure 6.

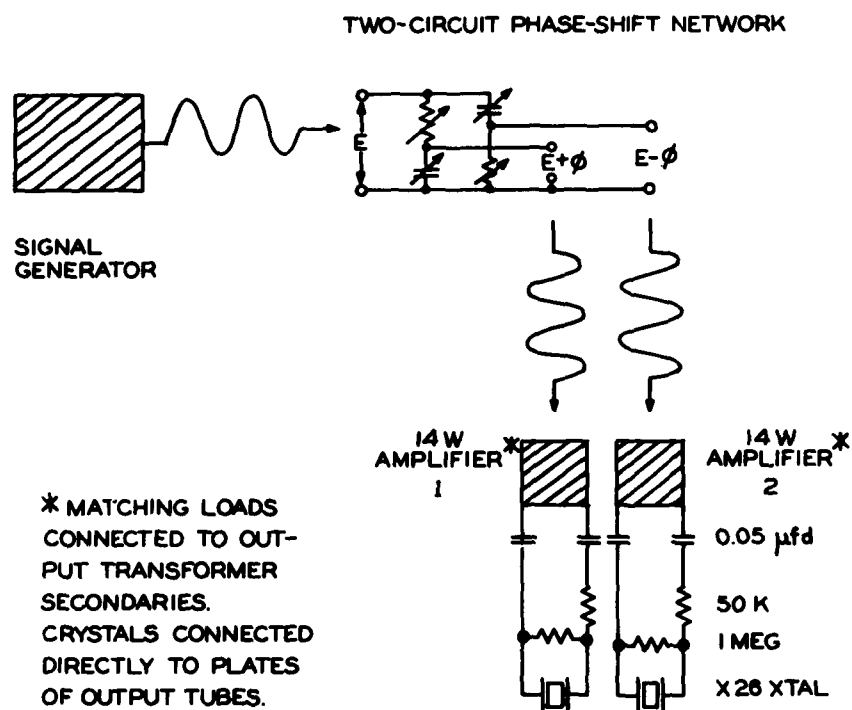


Figure 4. Diagram of Crystal Drive Circuit

The patterns formed in the manner described above may be enlarged or reduced by varying the input voltage to the transducers. If this variation takes the form of a modulation at some sub-harmonic of the frequency of crystal excitation, a longer time is available for the operation of shutters and other auxiliaries, since the recording medium may be masked so that a single record is produced once during each sub-harmonic period rather than once each natural period. A simpler apparatus may be used when the sub-harmonic input is added to the natural-frequency transducer input, with essentially the same effect. If, for example,

the sub-harmonic is added to the input of the transducer which deflects the light beam along the minor axis of an ellipse, the effect will be an overall sinusoidal displacement of the elliptical figure along its minor axis. Simple resistive adding networks may be used for this purpose instead of the electronic gain-control circuits required for modulation. In addition, the resistive net is essentially distortionless, whereas the modulation circuitry may be made to have low distortion only with considerable effort, particularly as the modulation frequency approaches that of the carrier.

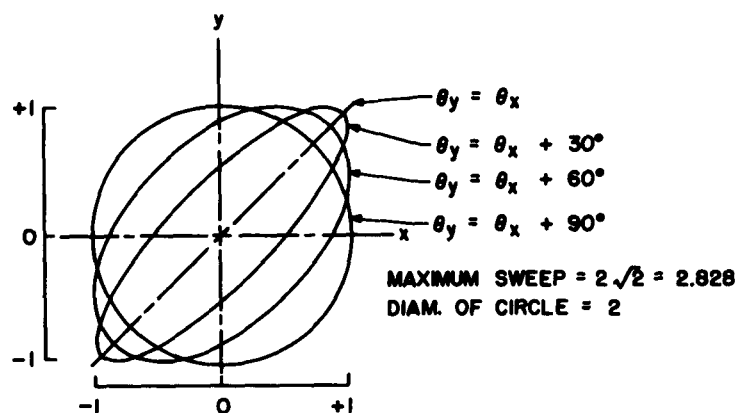


Figure 5. Figures Produced by Vibrating Mirror Pairs - $\sin \theta_x$ and $\sin \theta_y$, x and y Axes Perpendicular

$\sin \theta_x$ AND $\sin \theta_y$, x AND y AXES PERPENDICULAR

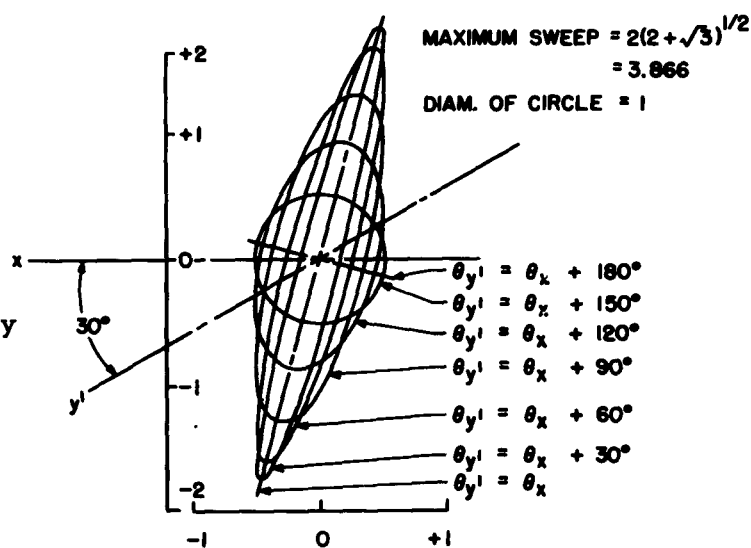


Figure 6. Figures Produced by Vibrating Mirror Pairs - $\sin \theta_x$ and $\sin \theta_{y'}$, x and y' Axes at 30°

$\sin \theta_x$ AND $\sin \theta_{y'}$, x AND y' AXES AT 30°

Jitter-free (and therefore reproducible) patterns can be formed by using sub-harmonics as low as the fourth to shift the figure, without introducing the possibility of slit rewrite. Although a small amount of roll was present in the figures, this was due to the fact that separate oscillators supplied the excitations of differing frequency. The roll could be eliminated by the use of a multivibrator or tuned-harmonic circuit to supply a second signal synchronized with the first.

Figure 7 shows patterns made by the sub-harmonic addition technique. The response of the cartridges to such complex waveforms is described by the frequency response to the components of the complex wave. This was studied, and can be seen in another result shown in Figure 8: a square wave at one-third the natural frequency of the crystal was used as the input to an oscillating-mirror resolver. A streak record of the output is shown in the figure, and shows the expected rounding caused by attenuation of Fourier components above the third harmonic of the square wave (the natural frequency of the crystal) and is almost identical to the predicted fundamental-plus-third-harmonic square-wave approximation.



Figure 7a. Response of X26 Resonant-Modified Crystal Transducers -
Major Axis: 3450 cps, 150 V rms -
Minor Axis: 3450 cps, 100 V rms,
 $90^\circ \phi$, Plus 862.5 cps, 50 V rms



Figure 7b. Response of X26 Resonant-Modified Crystal Transducers -
Major Axis: 3450 cps, 150 V rms -
Minor Axis: 3450 cps, 100 V rms,
 $90^\circ \phi$, Plus 1725 cps, 50 V rms



Figure 8. Streak Record of X26 Crystal Response
to 1150 cps Square-Wave Excitation

Several methods of introducing non-recurring electrical transients into the transducer input were investigated. These have been used to shift the image of the event onto the recording medium at the time desired, producing pulse effects somewhat like that of the periodic displacement of the scanning figure described earlier.

A momentary increase of amplitude can be obtained by adding the output of a damped oscillator in resonance with the continuous-wave crystal excitation at a predetermined time. The block diagram of such a system is shown in Figure 9, together with the waveforms produced in the successive stages of the system. The circuit of Figure 10, which performs the squarer, differentiator, trigger, ringing

and delay, and summation functions, was constructed. A typical waveform appearing at the transducer input is shown in Figure 11.

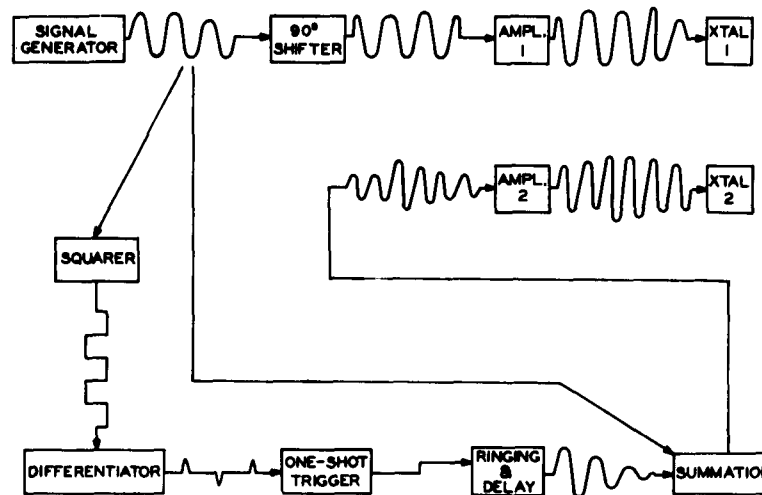


Figure 9. Block Diagram of Momentary Sine-Wave Amplitude-Increase Circuit

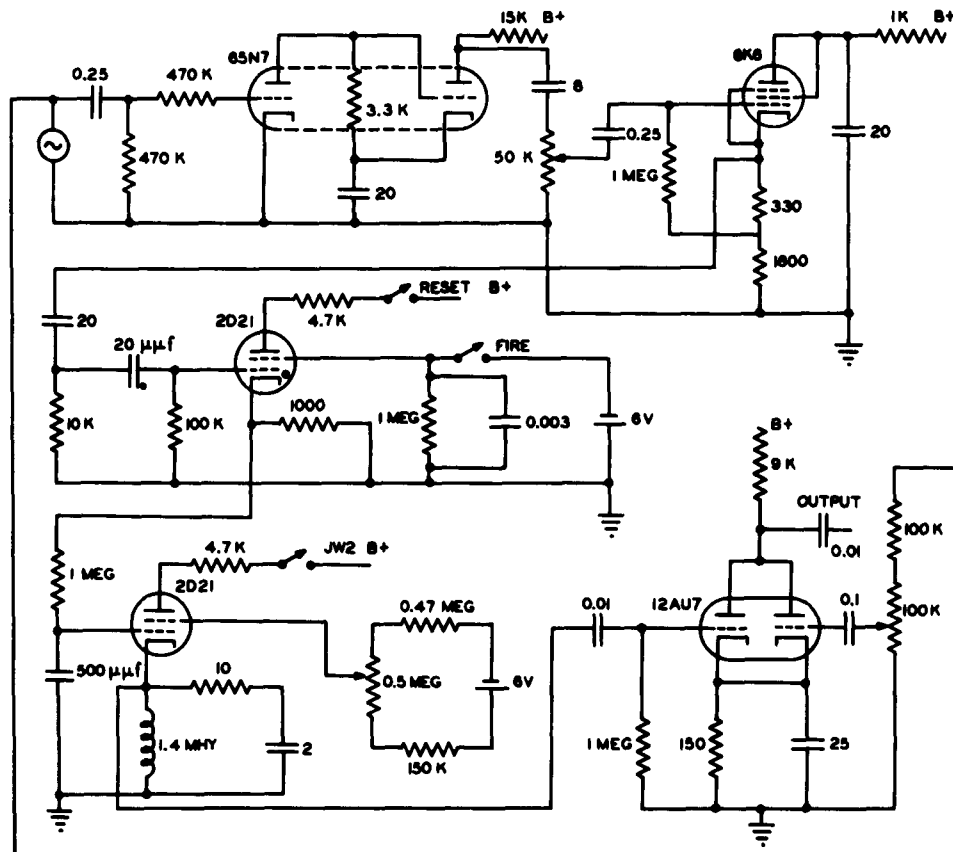
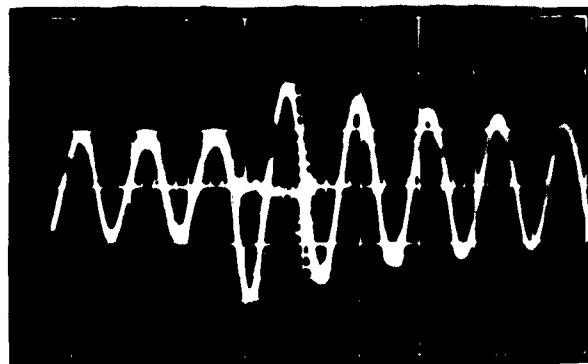


Figure 10. Squarer, Differentiator, Trigger, Ringing and Delay, and Summer Circuit

Figure 11. Momentary Sine-Wave Amplitude-Increase Circuit: Output Waveform



A sharp step-function could be used in analogous fashion to move the crystal from rest upon receipt of a signal, sweeping an image over the recording medium. The circuit of Figure 12 produces the step shown in Figure 13 with a rise-time of less than 0.1μ second. A streak record of the response of an X26 resonant-modified crystal to this excitation is shown in the streak-camera record of Figure 14.

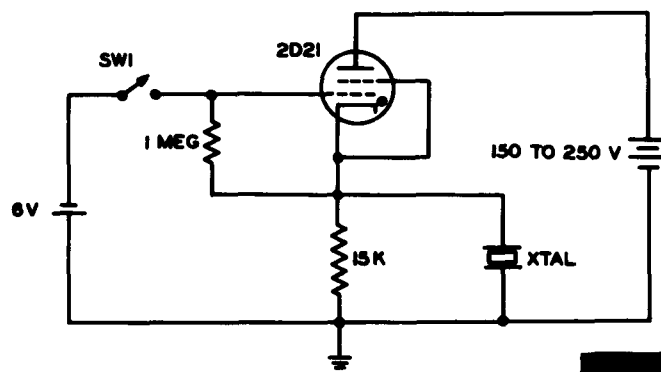


Figure 12. Sub-Microsecond Step-Function Generator

Figure 13. Output of Sub-Microsecond Step-Function Generator - Vertical: 50 V/cm - Horizontal: 1μ sec/cm

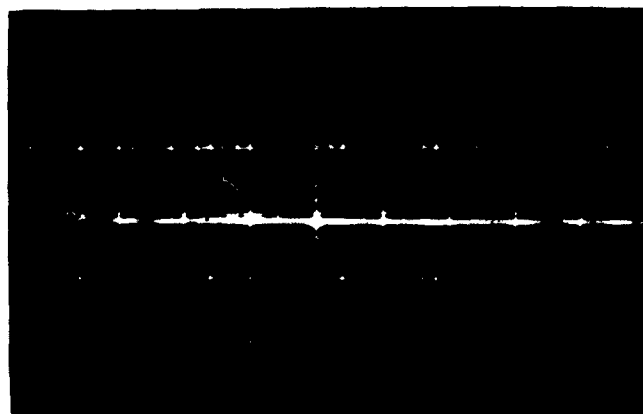
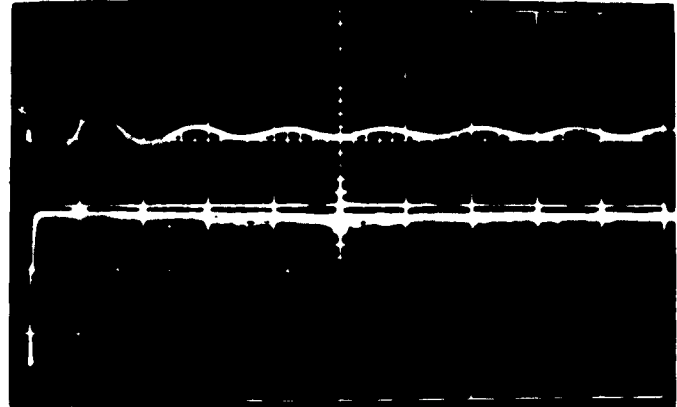


Figure 14. Response of X26 Resonant-Modified Crystal to Step-Function of Figure 13

A photomultiplier was used in a study of the possibilities of obtaining a single spot motion over a spectrograph slit in response to transient magnitude-increase of a continuous-wave transducer excitation. The photomultiplier slit was placed just beyond the point of maximum spot deflection under continuous-wave excitation which would be the position of the spectrograph slit in the intended use. A successful single sweep was repeatedly obtained upon the application of transient gain increase. An oscilloscope trace of the transducer input and a photomultiplier output is shown in Figure 15.

Figure 15. Oscilloscope Display of Transient Magnitude-Increase of Continuous-Wave Transducer Input at 3450 cps (Upper Trace) - Corresponding Output of Photomultiplier Off Axis (Lower Trace) Indicating Single Spectrograph Slit Sweeps Can Be Obtained Using This Type of Excitation



4. Ancillary Devices

It can be foreseen that under many circumstances it would be desirable to obtain an electrical pulse for use in triggering an event or device external to the vibrating mirror system, such as a shutter or timing circuit, in reproducible synchronism with some portion of the resolver oscillations. The circuit shown in Figure 16 is a trigger which has been constructed for this purpose, and is shown in connection with a xenon flashtube circuit at the right of the figure. If a visual indication of the point of triggering is required, the level control of the circuit is adjusted to a relatively insensitive position and the input is connected to the "trigger-out" jack of an oscilloscope having a single-sweep feature. The circuit level control is then adjusted to fire the thyatron on receipt of the trigger-out pulse. Synchronization is effected with the oscilloscope trigger level and stability controls, and the point of synchronization is displayed on the CRT, showing as the point of sweep initiation.

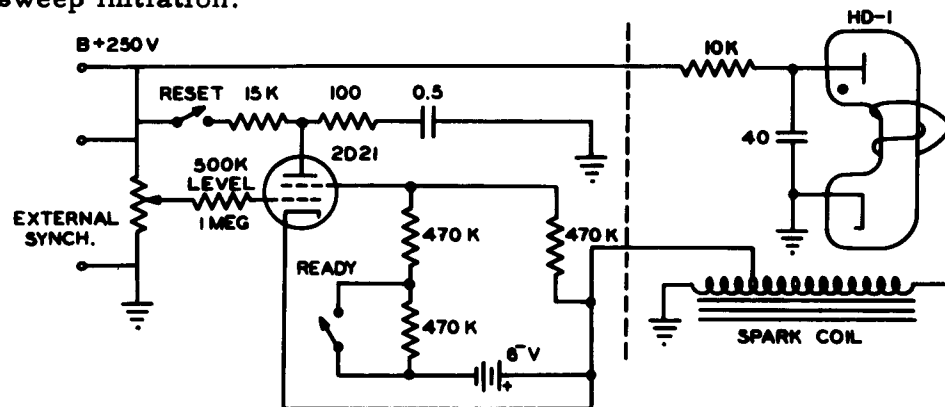


Figure 16. Synchronizing Trigger and Flashtube Circuit

A circuit similar to the trigger described above, but having greater current-handling capacity, was used to explode tungsten-filament bulbs in reproducible synchronism with the resolver motion. The apparatus is shown in Figure 17. The optical system employed is the positive-negative combination described previously, and the bulb illuminates a horizontal slit which serves as the object. The resolving transducers are driven at 150 or 250 v rms at the natural frequency of the transducers, 3450 cycles per second, and produce an elliptical deflection pattern through their interaction along axes separated by about 30° in the plane perpendicular to the beam axis. An 85-mm focal length cylindrical lens intercepts this beam and condenses it in the horizontal direction; a vertical knife-edge blocks half of the elliptical sweep at the cylindrical lens. The resulting pattern at the spectrograph slit is a spot of light which appears intermittently once during each cycle of transducer motion, and scans in essentially straight-line vertical motion. The spot is on the order of 50 to 100 microns in width, which allows the use of the spectrograph in the slitless mode; this yields the benefit of fairly good wavelength resolution and uniform spectral response characteristics as the spot traverses the slit aperture, without requiring achromatic optics and fine registration of the sweep and slit.

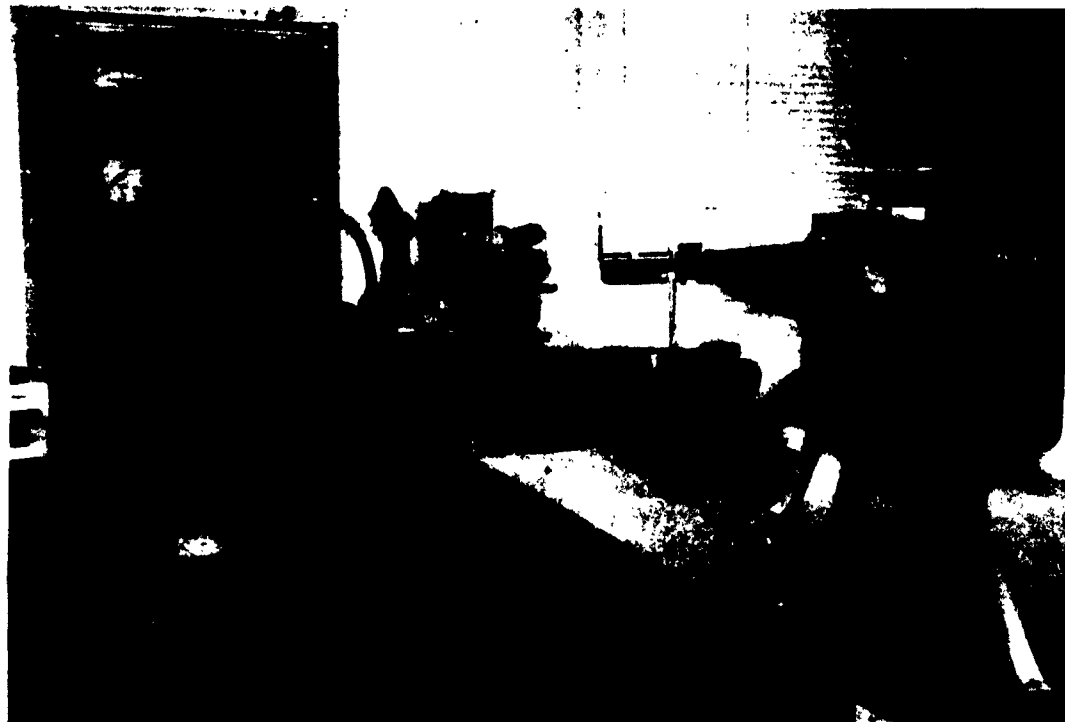
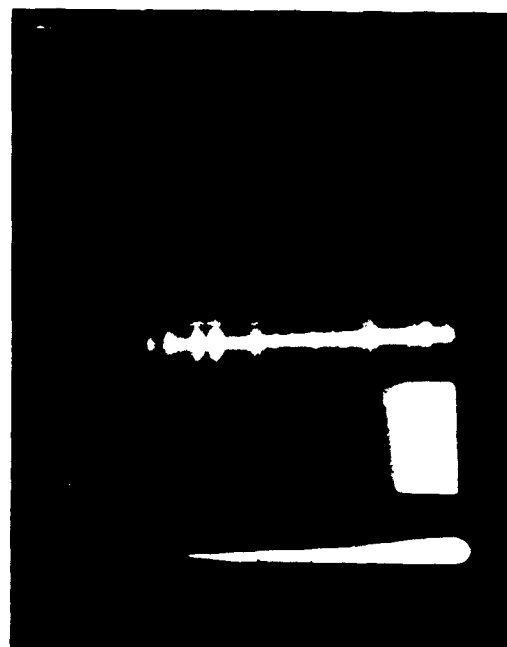


Figure 17. Apparatus Used in Obtaining Spectrograms Employing Piezoelectrically-Driven Resolvers

Figure 18 is a spectrographic record of a succession of events, made with the apparatus described above. The top trace is a sweep spectrogram of an exploding No. 47 tungsten filament bulb at an applied emf of 250 volts. The second trace is a similar record with the firing trigger adjusted to record a different portion of the filament destruction. The entire height of each trace represents approximately

one millisecond, and a resolution of about 50 microseconds is obtained. The third trace records an exploding filament, but with the resolving sweep disabled. The exposure is the same as the upper traces, therefore the spot size—particularly at the longer wavelengths—is exaggerated by overexposure; true impression of this dimension can be obtained through inspection of the shorter wavelengths. The spread of spectral lines is due to overexposure and chromatic aberration (particularly in the blue and violet) which could be eliminated through the use of an achromatic negative lens. The fourth trace is a sweep-record of a No. 47 bulb illuminated continuously at its rated emf of 6.3 volts, and illustrates the uniformity of exposure obtained as the beam sweeps the slit. The last trace is similar to the fourth except that the sweep is disabled, and shows many of the points enumerated in connection with the third trace, except that the shorter-wave emission from this lower-temperature source is, of course, much lower in intensity.

Figure 18. Ordinary and Time-Resolved Spectrograms of Exploding and Continuous-Burning Tungsten Filaments Obtained Using Piezoelectrically-Driven Resolvers



5. High-speed Optical Recording Devices Now in Use

A literature survey was conducted to determine the present state of high-speed camera techniques and to permit ready access to the designs and experience of other investigators. Photocopies have been made of the more significant articles; those of lesser interest are abstracted, with sketches of any unusual principles or mechanisms. The search is being continued to keep the bibliography up-to-date as well as to increase its scope.

A Los Alamos Model 6 turbine was run at speed to check the proper operation of the control circuitry and the turbine-mirror itself. The turbine and lubrication system is of the conventional type;⁽¹³⁾ the electrical and pneumatic controls were specially designed and built by the University of Dayton Research Institute to provide interlocks to insure safe operation of the turbine in the event of component failure or operator error.

Traditionally, high-speed mirror tachometry has been accomplished by magnetizing the mirror and picking up flux changes due to mirror rotation with a coil. This method gives only a sinusoidal output and is often sensitive to 60-cycle hum and other stray fields; in addition, the mirror may accumulate ferrous filings and dust. A tachometer giving pulses at definite points corresponding to one or more mirror positions would be more useful as a speed-measuring device.

The sound waves produced by the mirror motion were detected with a microphone and displayed on an oscilloscope. It was found that considerable vertical and horizontal jitter is present, and a rather complex waveform is characteristic. Sonic tachometer pickup might be useful in some applications, but is definitely inferior to the optical pickup described below:

A beam of light from a slit was imaged by a lens and reflected from the moving mirror. This beam passed through another slit to a photomultiplier when a specific point in the rotation of the mirror was reached. A CRT display of the pulses was obtained on an oscilloscope, and digital readout was given by an EPUT meter. A frequency discriminator giving a meter indication of pulses-per-second or percent deviation from a given frequency was also investigated, but was found to be difficult to use at higher turbine speeds or over a wide range of speeds since frequent realignment of the instrument is needed. The oscilloscope and EPUT give more information and appear to be easier to use and are more reliable in their operation.

The optical tachometry system was used to monitor the turbine speed during several runs, and it was found that with a small amount of practice the gas pressure regulator could be manually adjusted to hold the turbine speed essentially constant for periods up to a second or longer. This fact, previously unknown, has several implications: (1) It may be possible to use some type of automatic pressure regulator to maintain a constant, pre-set turbine speed. (2) The tachometer lamp may be shut off, using a Compur-type or other relatively slow shutter, several milliseconds before the use of the mirror-turbine in data recording. This procedure prevents possible interaction of the event and the tachometer system, but with good assurance that the writing rate remains essentially the same as when measured a fraction of a second previously. (3) The principal type of turbine-speed variations may be those which occur over a period of one revolution of the mirror or less; this fact becomes increasingly important as mirrors with large numbers of faces are used to increase framing rates.

In accordance with the third implication stated above, a study was made to determine whether such short-period flutter exists to a measurable extent. The optical system was modified to give an additional pulse to another photomultiplier and slit as the turbine rotated. The second slit traversed about the mirror axis, and the pulse spacings obtained were compared with the angles separating the photomultipliers. It was found that no gross amount of measurable flutter exists.

The high-speed mirror-turbine is presently being used as a reference standard in speed comparisons and as an accurate high-speed optical pulse generator to measure speed and time-resolving power of other optical recording systems.

A Courtney-Pratt, (23, 24) high-speed image-dissection camera was obtained, and the original British design has been Americanized to permit use with standard line voltage and cabling. A control panel has been built to permit easy operation and accurate tachometry. This camera will be used in studies of resolver motion and the transmission of vibration from electromechanical transducers to the moving mirrors.

BIBLIOGRAPHY

1. Sykes, W., "Study of Fast Events," Science, Vol 130, No 3382, pp 1051 ff, 23 October 1959.
2. Mason, W., Piezoelectric Crystals and Their Applications to Ultrasonics, Van Nostrand, 1950.
3. Mason, W., Physical Acoustics and the Properties of Solids, Van Nostrand, 1958.
4. Mason, W., Electromechanical Transducers and Wave Filters, Van Nostrand, 1948.
5. Richardson, E., Technical Aspects of Sound, Elsevier, 1957.
6. Hueter, T., and R. Bolt, Sonics, Wiley, 1955.
7. Milne, G., W. Staudenmaier, and T. Putnam, Study of Streak Spectrograph Designs for the Visual and Ultraviolet Spectral Regions, Interim Report, ONR Contr. 1799(01), Inst. of Optics, University of Rochester, Department of the Navy.
8. Milne, G., W. Staudenmaier, and T. Putnam, Study of Streak Spectrograph Designs for the Visual and Ultraviolet Spectral Regions, Final Report, ONR Contr. 1524(00), Inst. of Optics, University of Rochester, Department of the Navy.
9. Aller, Astrophysical Quantities.
10. Loneragan, R., The Spectral Absorption of Kerr Cell Shutter Materials in the Photographic Region, ARDE Memorandum (MX)7/58, ASTIA Document No. AD-159412, Ministry of Supply, Materials Explosives Division.
11. Kodak High-Speed Films for Short Exposure Time Applications, Kodak pamphlet P-32, Eastman Kodak Company.
12. High Speed Camera Instrumentation Manual, Group J-15, Los Alamos Scientific Laboratory, pp 23-24, 1957 Edition.
13. High Speed Camera Instrumentation Manual, Group J-15, Los Alamos Scientific Laboratory, passim, 1957 Edition.
14. Brixner, B., "High-Speed Turbine-Driven Rotating Mirrors: Notes on Design, Construction, and Performance," Rev. Sci. Instr., Vol 30, No 11, pp 1041 ff, November 1959.

BIBLIOGRAPHY (CONT'D)

15. Brixner, B., "One Million Frame per Second Camera," J. Opt. Soc. Am., Vol 45, No 10, pp 876 ff, October 1955.
16. Brixner, B., "A Simple Sweeping-Image Camera (Chronograph) with 10^{-8} Second Revolution," High Speed Photography, Proceedings of the Third International Congress, Session XII, September 1956.
17. Brixner, B., "Fifteen-Million Frame Per Second Camera," Actes Du 2eme Congres International De Photographie Et Cinematographie Ultra Rapides, Paris, September 1954.
18. Beams, Linke, and Summer, Rev. Sci. Instr., Vol 9, p 248, 1938.
19. Buck, W., "High-Speed Turbine-Driven Rotating Mirrors," Rev. Sci. Instr., Vol 25, No 2, pp 115 ff, February 1954.
20. Robinson, E., "Stresses in Turbine Disk Wheels," Mechanical Engineers' Handbook, L. Marks, ed., p 477, McGraw-Hill Book Company, Inc., New York, N.Y., 1951.
21. Roark, R., Formulas for Stress and Strain, p 332, McGraw-Hill Book Company, Inc., New York, N.Y., 1954.
22. Clevite Components Corporation, Properties of PZT-5, Data Sheet.
23. Hayes, R., "Stopping High Speed Events at 250,000 Photos/Sec," Industrial Labs., Vol 6, No 9, September 1955.
24. Courtney-Pratt, J., and C. Huggins, "Construction and Performance of a High-Speed Cinemicrograph," Rev. Sci. Instr., Vol 28, No 4, pp 256 ff.

University of Dayton Research Institute, Dayton, Ohio. HIGH SPEED RECORDING BY RESONATING OPTICAL RESOLVERS by W. R. Rambauske and R. H. Keith. December 1961. 29p. incl. illus. (Project 7073; Task 70712) (Contract AF 33(616)-6766 (ARL 147) Unclassified Report The application and design of resonant elements for high-speed spectrographic and camera work seems to be a unique new approach to specific tasks of the analytical physicist, and should provide a useful experimental instrument for the laboratory on earth and in space. Inexpensive construction and ease of operation characterize the new device, which has a time-resolution capability similar to the customary high-speed helium turbine drives with little or none of their operating difficulties. The findings of this preliminary investigation indicate that further study of the properties and applicability of oscillating drives should be of benefit.	UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED
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