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A ROTARY DOPPLER SIMULATOR FOR OPTICAL FREQUENCIES

Donald C. Thorn
Thomas R. Erney
Burton J. Smith
Donald E. Morris

University of New Mexico
Bureau of Engineering Research
Albuquerque, New Mexico 87106

Contract AF 29(601)-7097

TECHNICAL REPORT NO. AFWL-TR-66-117
February 1967

AIR FORCE WEAPONS LABORATORY
Research and Technology Division
Air Force Systems Command
Kirtland Air Force Base
New Mexico

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FOREWORD

This report was prepared by the Bureau of Engineering Research, University of New Mexico, Albuquerque, New Mexico, under Contract AF 29(601)-7097.

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This technical report has been reviewed and is approved.

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ABSTRACT

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A device that generates a doppler shift, comparable to the optical reflections from a target moving with constant velocity, without any net translational movement, has been produced.

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ILLUSTRATIONS

SECTION I

INTRODUCTION

A large number of optical frequency devices, currently in prototype or earlier stages of development, use a single laser as both transmitter and local oscillator. In such an arrangement, the intermediate frequency is generated by the target-induced doppler shift inherent in system operation. Although such an arrangement has many merits as an operational device, it has the disadvantage that static tests cannot be performed on it.

This report describes a device that has the property of producing, without any net translational movement, a doppler shift comparable to that associated with reflection from a target moving at a fixed velocity.

SECTION II

THE CURVE

Required is a rotating, mirrored surface (Fig. 1), having two properties relative to a specific ray:

(a) The surface of the mirror must be, for all angular positions, normal to the ray at the point of intersection of the ray and the mirror. That is,

$$\frac{dy}{dx} = \tan \alpha \tag{1}$$

(b) The locus of the intersection of the ray and the mirror must move along the ray at a velocity directly proportional to the rotational velocity of the mirror assembly. That is,

$$\frac{da}{dt} = C\,\frac{d\alpha}{dt} \tag{2}$$

We must solve for the surface shape y(x) in a way to meet these requirements.

After a fairly involved derivation, it was found that the curve that defines the desired surface is the involute of the circle. The involute of the circle is described by the parametric equations

$$x = K(\cos\alpha + \alpha\sin\alpha) \tag{3}$$

$$y = K(\sin\alpha - \alpha\cos\alpha) \tag{4}$$

where the symbols are defined in Fig. 1. Let us demonstrate that the conditions of Eq. (1) and Eq. (2) are met.

The condition imposed in Eq. (1) can be studied by considering

$$\frac{dy}{dx} = \frac{\frac{dy}{d\alpha}}{\frac{dx}{d\alpha}}$$

From Eq. (4)

$$\begin{aligned}\frac{1}{K}\frac{dy}{d\alpha} &= \cos\alpha - \cos\alpha + \alpha\sin\alpha\\ &= \alpha\sin\alpha\end{aligned}$$

and from Eq. (3)

$$\begin{aligned}\frac{1}{K}\frac{dx}{d\alpha} &= -\sin\alpha + \sin\alpha + \alpha\cos\alpha\\ &= \alpha\cos\alpha\end{aligned}$$

Therefore, $\dfrac{dy}{dx} = \dfrac{\sin\alpha}{\cos\alpha} = \tan\alpha$

Next, consider the condition imposed by Eq. (2). We know from the geometry of Fig. 1 that

$$K^2 + a^2 = x^2 + y^2$$

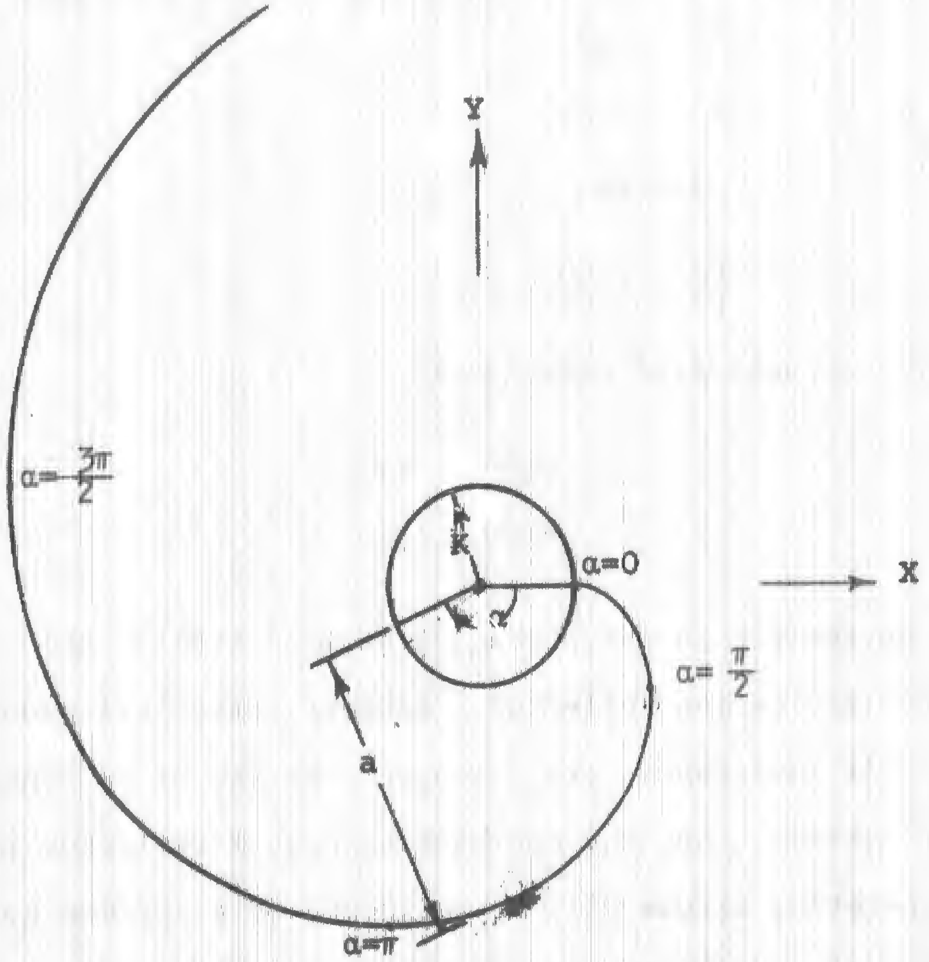

Figure 1. The Involute of a Circle

and so

$$
\begin{aligned}
a^2 &= x^2 + y^2 - K^2 \\
&= K^2(\cos \alpha + \alpha \sin \alpha)^2 + K^2(\sin \alpha - \alpha \cos \alpha)^2 - K^2 \\
\frac{a^2}{K^2} &= \cos^2 \alpha + 2\alpha \sin \alpha + \alpha^2 \sin^2 \alpha + \sin^2 \alpha \\
&\qquad - 2\alpha \sin \alpha \cos \alpha + \alpha^2 \cos^2 \alpha - 1 \\
&= \alpha^2
\end{aligned}
$$

Therefore*

$$a = K\alpha$$

$$\frac{da}{dt} = K \frac{d\alpha}{dt} = K\omega$$

and Eq. (2) is satisfied with $C = K$.

SECTION III

THE DEVICE

The derivation in the preceding section treated the "inside" of the involute as the reflector. However, practical problems of strength, air resistance, etc., suggest the use of an "outside" reflector surface. Any ray approaching such a reflector tangent to the generating circle will be reflected by a surface normal to the ray and at a distance varying with the angle. Thus, as the reflector rotates at a fixed speed, the reflected signal experiences a doppler shift equal to that generated by a reflector with a linear velocity equal to the product of K and the angular velocity.

Any well collimated beam striking a convex cylindrical surface such as that described above will experience a divergence in the plane of the curvature. The character of this divergence will

---

*The negative root gives a mirror-image solution.

depend upon the radius of curvature (R) and the center of curvature (h,k) of the involute. In order to calculate these, we need the first and second derivatives of y(x). We have previously demonstrated that

$$\frac{dy}{dx} = \tan \alpha \tag{4}$$

and

$$\frac{d^2y}{dx^2} = \frac{d}{dx}\,(\tan \alpha)$$

$$= \frac{\frac{d}{d\alpha}(\tan \alpha)}{\frac{dx}{d\alpha}}$$

Since

$$\frac{d}{d\alpha}\,(\tan \alpha) = \sec^2 \alpha$$

and

$$\frac{dx}{d\alpha} = K\alpha \cos \alpha$$

then

$$\frac{d^2y}{dx^2} = \frac{1}{K\alpha \cos^3 \alpha}$$

The radius of curvature R is given by

$$R = \frac{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}}{\frac{d^2y}{dx^2}}$$

$$= K\alpha$$

$$= a$$

We can similarly determine the center of curvature (h,k).

$$h = x - \frac{\frac{dy}{dx}\left[1 + \left(\frac{dy}{dx}\right)^2\right]}{\frac{d^2y}{dx^2}}$$

$$= K \cos \alpha$$

$$k = y + \frac{1 + \left(\frac{dy}{dx}\right)^2}{\frac{d^2y}{dx^2}}$$

$$= K \sin \alpha$$

Thus we conclude that the involute mirror is such that the center of curvature is always on the generating circle at the point of tangency of the extended central ray of the reflected beam. The radius of curvature is such that the reflecting surface can be approximated by a circle intersecting the mirror at the point of reflection of the central ray. With such an approximation, we can estimate the angle of divergence shown in Fig. 2.

Consider a circle of radius R from which an ideally collimated beam of radius bR is reflected. The extreme rays of the incoming beam define an angle φ such that

$$\varphi = \sin^{-1} \frac{b}{R}$$

$$\doteq \frac{b}{R}$$

The extreme rays of the reflected beam diverge at the double angle, 2φ. Thus, the full beam divergence β is given by

$$\beta = 4\varphi$$

$$\doteq \frac{4b}{R}$$

Since R is time varying, the divergent beam appears to emanate from a moving point. Thus an attempt to use a recollimating lens will require an approximation.

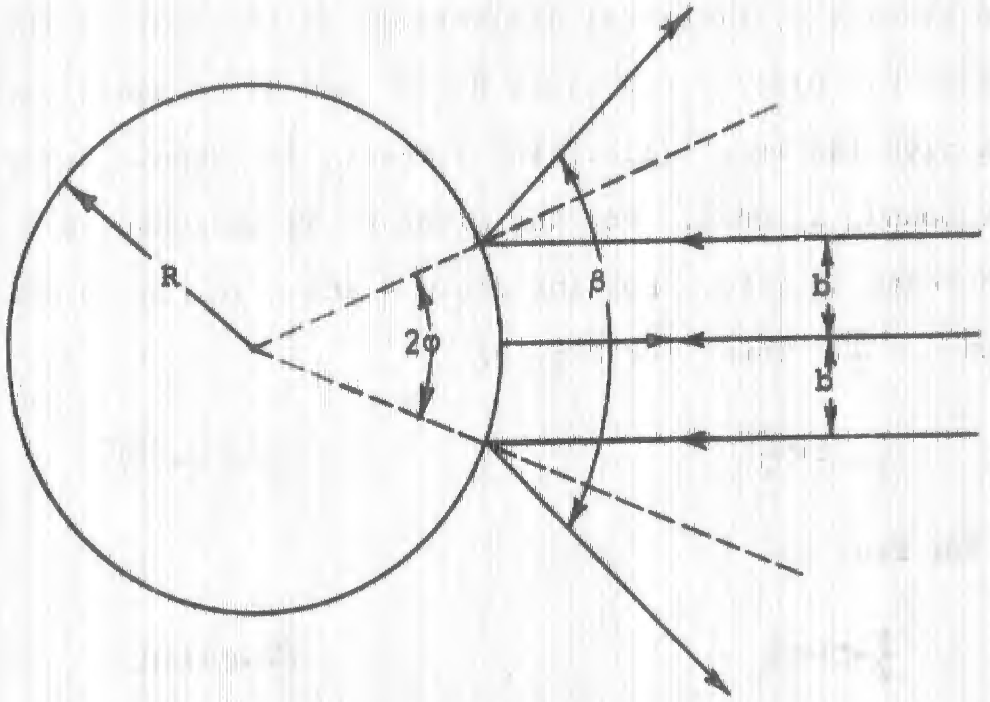

Figure 2. Divergence Geometry
(angles greatly exaggerated)

In preparing a final design for a doppler simulator of this type, there is an engineering compromise between size, beam divergence and the ratio of simulated linear speed to rotational speed. A further consideration is the number of "flyback" discontinuities per revolution. Two of these discontinuities are labeled "D" in Fig. 3 and 4. Since the divergence of the beam will be determined by the curvature in the neighborhood of the reflection, the radius K should be large compared to the beam diameter. Although an increase in K also increases the moment of inertia and thus the speed stability, practical limitations on the size of the simulator restrict K. Since $\alpha = 0$ gives $R = 0$, and since small values of $R = a$ give the worst (i.e., the largest) divergence, we place a lower bound, θ, on α. For any given K, an increase in θ generates an increase in size. For the designs shown in Fig. 3 and 4, we have chosen $\theta = \frac{\pi}{2}$. Thus, for Fig. 3,

$$\frac{\pi}{2} < \alpha < \frac{3\pi}{2} \qquad\qquad \frac{K\pi}{2} < R < \frac{3K\pi}{2}$$

and, for Fig. 4,

$$\frac{\pi}{2} < \alpha < \pi \qquad\qquad \frac{K\pi}{2} < R < K\pi$$

There will be some improvement in the divergence-size relationship if it is possible to have several discontinuities per revolution. Obviously, at least one such discontinuity is necessary; and, for purposes of mechanical balance, at least two are desirable. As the number of discontinuities (and hence the number of "lobes") is increased, the ratio of maximum to minimum radius decreases. This will decrease the variation of the divergence but does so at the expense of increasing the number of phase disruptions experienced per revolution. Some equipment under test may be disturbed by

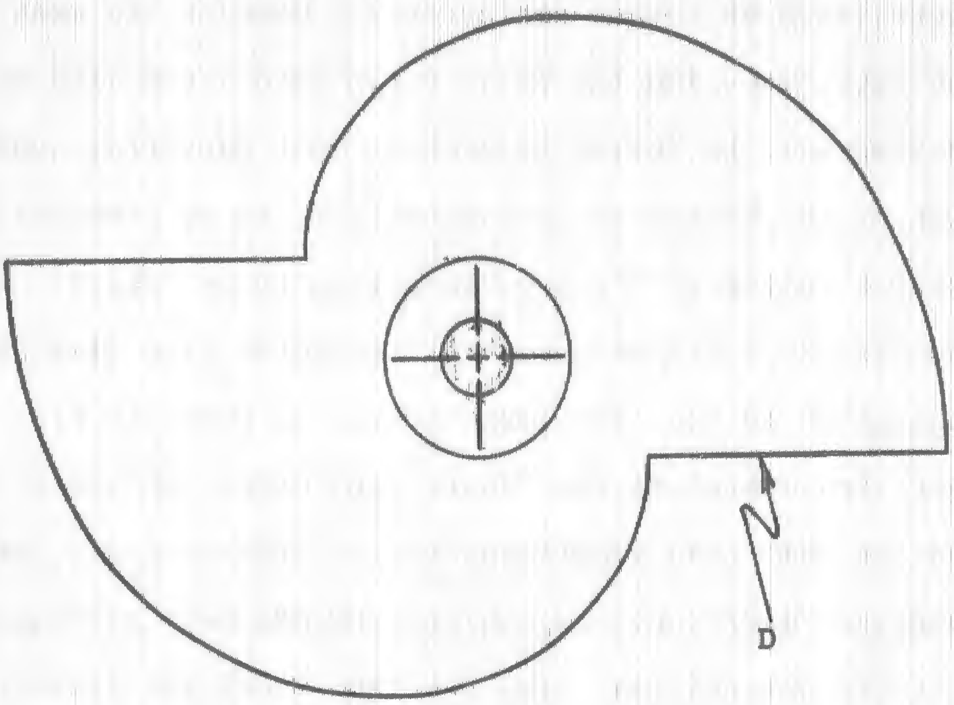

Figure 3. Two-Lobe Simulator Profile (1/2-scale)

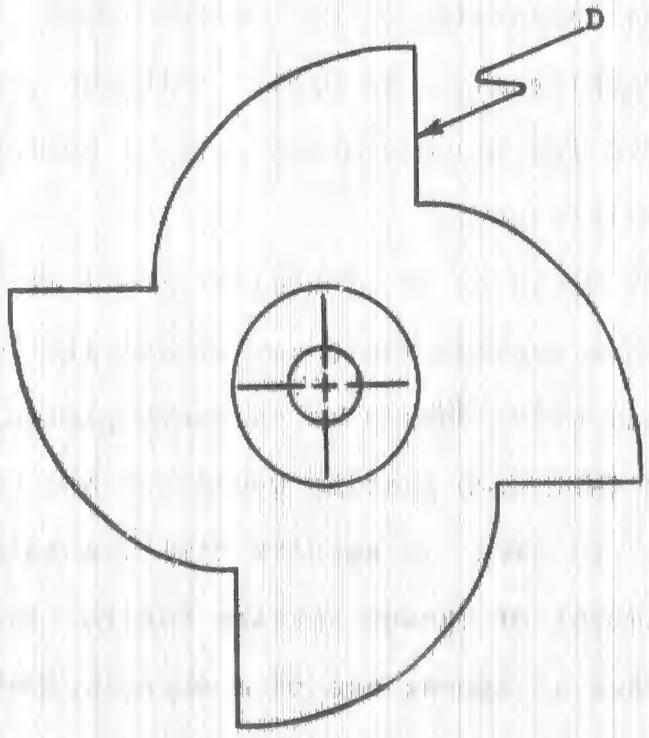

Figure 4. Four-Lobe Simulator Profile (1/2-scale)

these sudden phase changes, especially in systems using cooperating reflectors (such as corner reflectors). However, in most cases, both the divergence and the phase shift associated with the discontinuities will be fairly typical of most operating conditions. Selection of the number of discontinuities to be used will thus be largely a matter of the type of system to be tested.

Two different prototypes were fabricated from aluminium. One, designated as the "two-lobe" model, is shown in Fig. 3. The other, designated as the "four-lobe" model, is shown in Fig. 4. Both use the same size generating circle (radius K = 1 inch) and thus represent different compromises between beam divergence and number of discontinuities. The two-lobe model has primarily been retained for testing and for use in the Air Force Weapons Laboratory (AFWL) at Kirtland Air Force Base, while the four-lobe model has been used at The University of New Mexico (UNM). The two prototypes were built in machine shops at AFWL. Although produced on equipment not intended for manufacturing optical devices, these prototypes proved satisfactory.

Preliminary tests of the four-lobe model at UNM indicated that the aluminium surface would not retain its luster. It was decided that this model should be chromium plated, even though it was expected that such plating would further reduce the precision of the surface. In fact, it appears that the polishing and plating moderated the amount of random scatter due to small flaws, thereby giving the surface an appearance of a more accurate shape.

SECTION IV

TESTS AND RESULTS

The basic test setup used to evaluate the performance of the simulator is shown in Fig. 5; it consists of a Michelson interferometric arrangement, with the simulator acting as one of the reflective elements. A stationary mirror, a beam splitter, and a gas laser* used as a light source were all mounted on an optical bench. The simulator was driven by a variable speed motor through a speed-reducing gear train. This permitted extremely low rotational speeds. To help prevent motor and gear vibration from being coupled to the system, the entire drive assembly was shock-isolated from the optical bench. Although various detectors were employed, adequate results were obtained with a simple photo-emissive type whose output was fed into a conventional audio amplifier and loudspeaker. This combination facilitated the initial alignment of the optical system. For qualitative measurements, the signal was sampled and played back on a tape recorder with a continuous loop, which permitted detailed harmonic analyses to be made.

Because of the divergence of the beam after reflection from the simulator, it was necessary to minimize the distances from the beam splitter to the simulator and detector. When this requirement was met, it was possible to obtain a signal produced by the mixing of the original and doppler-shifted beams. The apparent translational velocity due to the simulator is

$$v = \frac{da}{dt} = K \frac{d\alpha}{dt} = K\omega$$

where K is the radius of the generating circle and ω is the rotational velocity of the simulator in radians per second. For the simulator

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*A helium-neon CW laser operating in the TEM_{00} mode at 6328 Å, with an output power of approximately 4.5 milliwatts and a beam divergence of less than 0.3 milliradians.

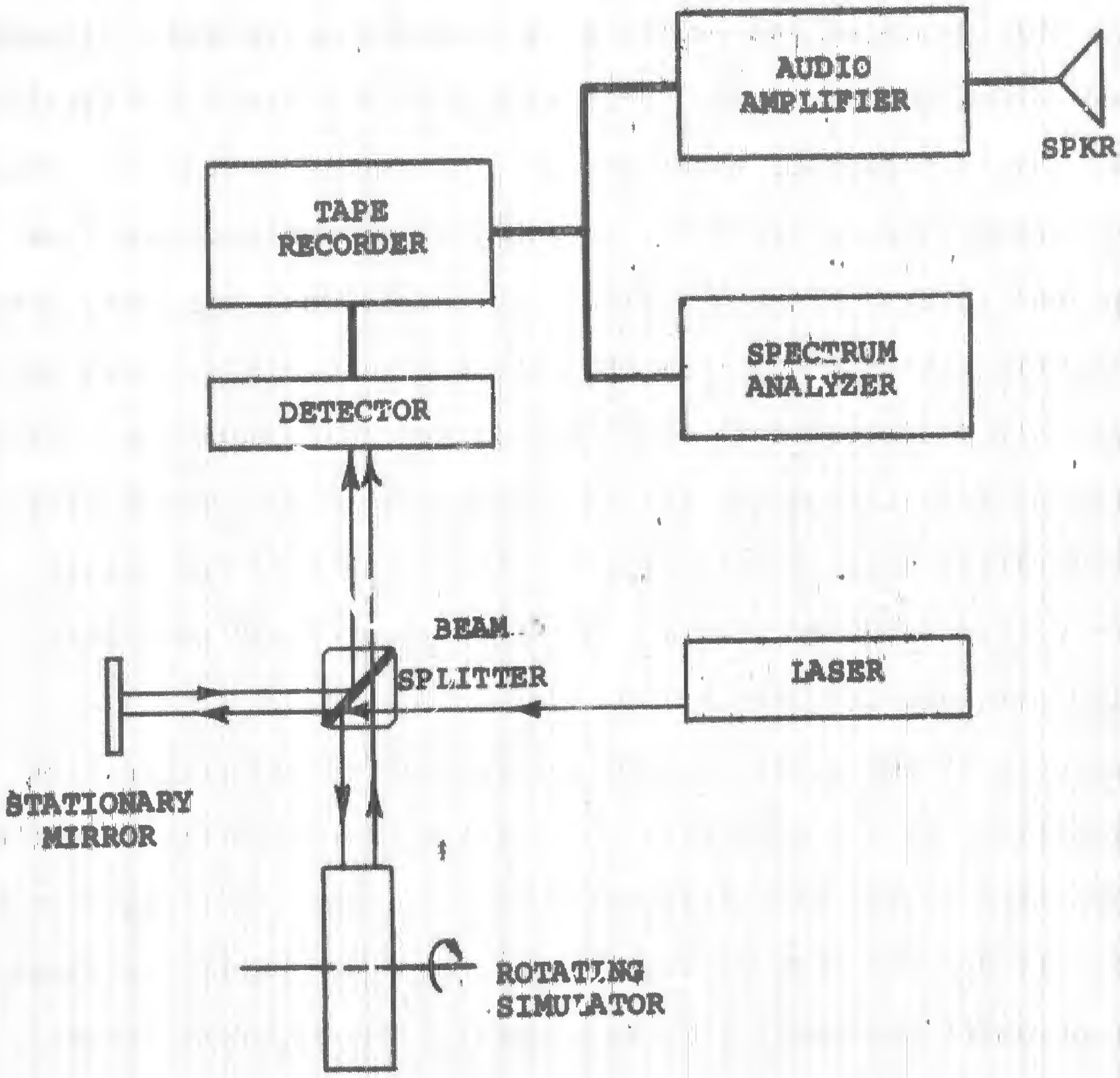

Figure 5. Test Equipment Configuration

under test, K = 1 in. Thus we have a simulation coefficient of*

$$1\ \frac{\text{in/s}}{\text{rad/s}} = 2.66 \times 10^{-3}\ \frac{\text{m/s}}{\text{r/min}}$$

In conjunction with the usual doppler equation

$$\Delta f = \frac{2v}{c} f_s$$

and with the basic laser beam (6328 Å) having a frequency of 4.74×10^{14} Hz, we obtain

$$\Delta f = 5.04 \times 10^5\ \frac{\text{Hz}}{\text{r/s}} = 8.40 \times 10^3\ \frac{\text{Hz}}{\text{r/min}}$$

Thus, in order to stay in the audible range, it was desirable to drive the simulator at less than 1 r/min.

When the simulator was turned at speeds in the range of 1 r/min an audio signal was produced, which is best described as sounding like a "tree full of singing canaries." This random chirping sound is almost certainly the result of frequency modulation due to surfac irregularities and some remaining mechanical vibration, and is expected to diminish in a more precisely built simulator. A representative analysis of the beat note resulting from turning the simulator at approximately 3/8 r/min resulted in the spectrum shown in Fig. 6. The frequency-modulated signal at 3.1 kHz is apparent. In order to reduce the effects of long-period amplitude variations due to gross irregularities in the simulator surface, the spectrum analysis was made from a 3.5-second sample of the beat note.

A similar analysis was made on the two-lobe simulator from AFWL. The resulting spectrum is shown in Fig. 7. The unplated surface of the two-lobe model should yield a lower signal-to-noise

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*Unit symbols in this report comply with the IEEE standards in <u>IEEE Spectrum</u>, pp. 113-115, August 1965.

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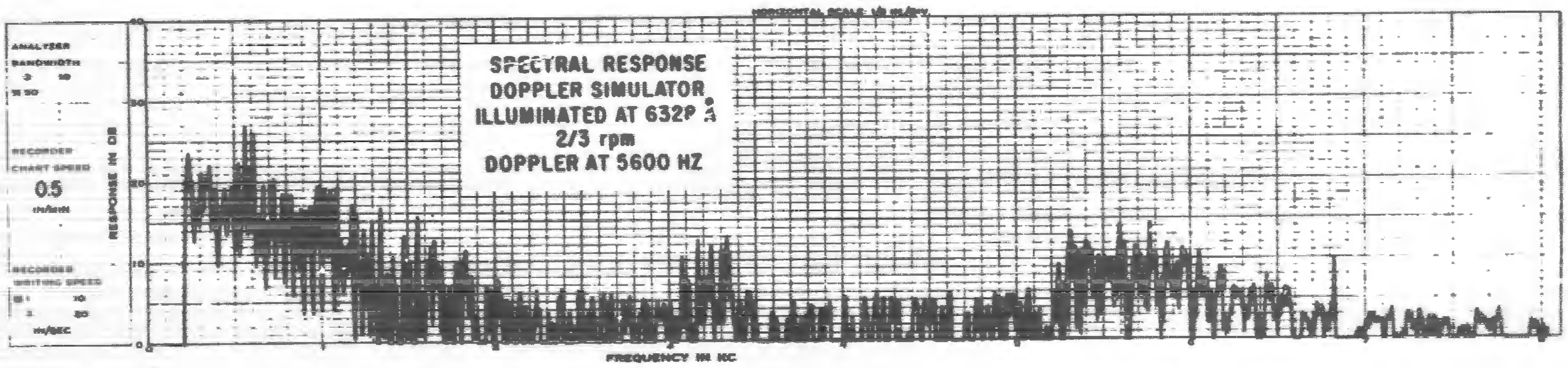

Figure 6. Frequency Spectrum: Four-Lobe Model

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ratio than the plated surface of the four-lobe model. However, the lower signal-to-noise ratio of Fig. 7 (as compared with Fig. 6) should not be construed as proof of this, since small, arbitrarily selected samples were used to produce the two spectra.

Both spectra show a component centered near 0.6 kHz. This component has been identified as a harmonic of a vibratory signal generated by the reducing gear train. Other harmonics of this signal were present in earlier analyses but were removed by shock-mounting the drive mechanism.

SECTION V

SUGGESTIONS FOR FURTHER WORK

Several possibilities for further development of the basic design suggest themselves. Of immediate interest, of course, is the production of a truly specularly surfaced simulator. Also, it might be possible to apply coatings to the device, to simulate closure with a variety of nonspecular surfaces. In a multilobed device it would be possible to use different coatings on adjacent lobes to give immediate comparisons. When extremely high closure rates are desired, it will probably be necessary to have a more detailed mechanical design to optimize structural integrity under high stresses. Also, it might be desirable to enclose the assembly in a protective housing containing a low-pressure gas to decrease "windage loss" and to allow higher rotational velocities.

In addition to the design tested, other shapes of "optical cams" are possible to give other effects. For instance, the problem of producing optical frequency chirp radar could be approached in this fashion.

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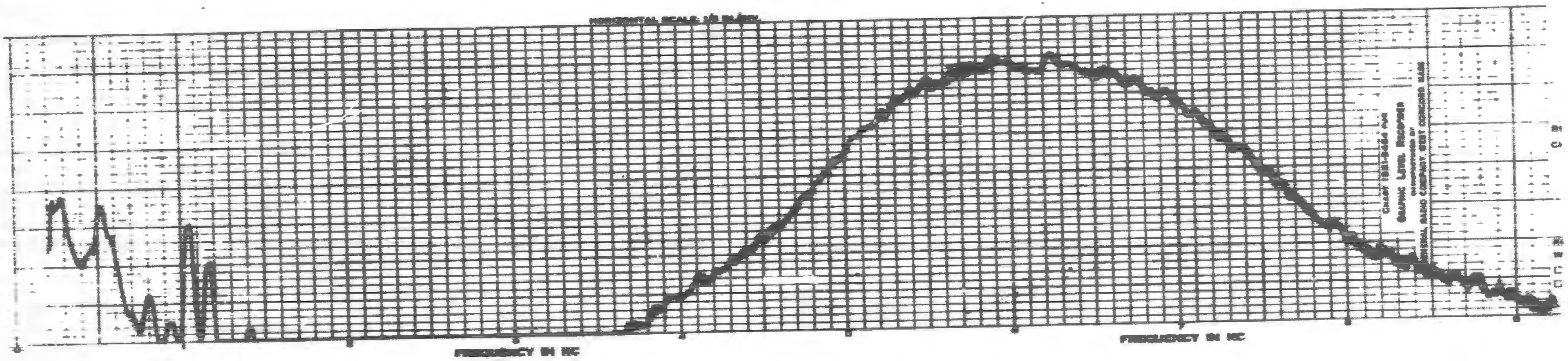

Figure 7. Frequency Spectrum: Two-Lobe Model

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SECTION VI

CONCLUSIONS

A doppler simulator suitable for optical frequency application has been fabricated and tested. Although the basic results indicate vibration and an optically rough surface, they demonstrate the validity of the technique for doppler shifting of optical signals.

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