We have found that if sinusoidal acceleration of $\frac{1}{4}$ to $\frac{1}{3}$ the rms value of the desired random vibration causes no noticeable distortion of the discriminator output, then the mechanical behavior is sufficiently linear for an accurate prediction of the frequency modulation which will result from a given random vibration.

The prediction of the frequency modulation caused by random vibration is simply a matter of evaluating

$$m = \left[\int_{\mu_1}^{\mu_2} [M(\mu)]^2 \psi(\mu) d\mu \right]^{1/2} \tag{2}$$

where

m = rms frequency deviation in the band μ_1 to μ_2
$M(\mu)$ = mechanical modulation coefficient
$\psi(\mu)$ = magnitude of the random acceleration density spectrum (in terms of g^2/cycle).

If neither $M(\mu)$ nor $\psi(\mu)$ vary appreciably between μ_1 and μ_2, then

$$m = M(\mu)[B\psi(\mu)]^{1/2} \tag{3}$$

where the bandwidth B is usually the bandwidth of the wave analyzer.

Figure 2 is a plot of the mechanical frequency modulation coefficient measured on one of these reflex klystrons. Note that this coefficient is less for vibration perpendicular to the beam axis than for vibration along the beam axis, as would be expected from a mechanical analysis of a cross-section view of a typical reflex klystron. This klystron was then operated under random vibration having the acceleration spectral density shown in Fig. 3. Note that the spectral density is given in terms of $[\psi(\mu)]^{1/2}$. The plot above 5 Kc/s is beyond the calibrated range of the accelerometer, and is included to show that vibration is present well beyond the cutoff point of the band-limiting filters used in the vibration gear.

Figure 4 is a plot of the frequency modulation measured under the random vibration of Fig. 3. For comparison, Fig. 2 and (2) were used to compute the circled points. Note that the data above 5 kc/s confirms that the tube responds to vibrations at ultrasonic frequencies. It can be seen that very accurate predictions of performance are possible. Care must be taken to ensure that the vibration input to the device under test is linear, and that distortion within the vibration equipment, both mechanical and electrical, do not introduce frequency compnents well outside the desired vibration range.

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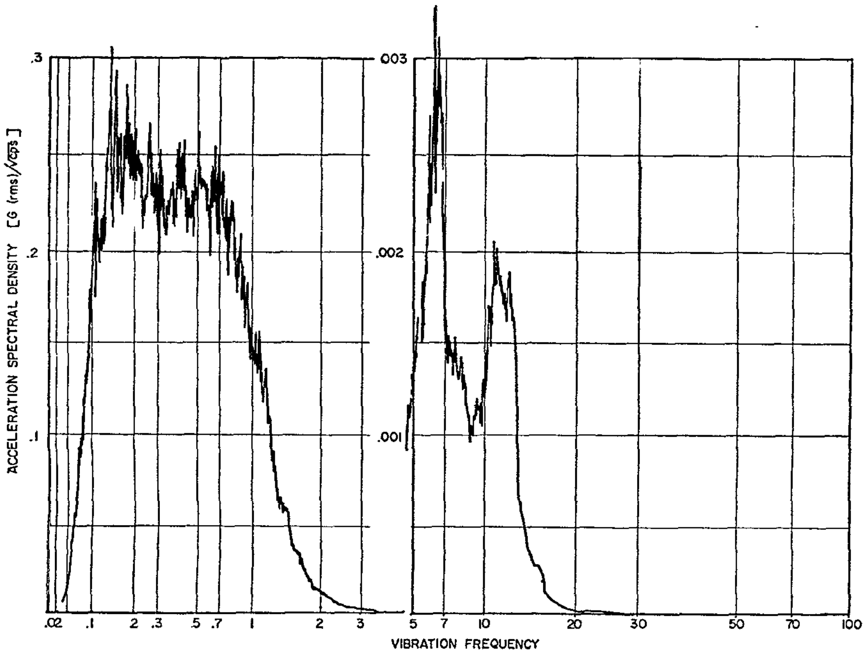

Fig. 3. Measured vibration spectral density (accelerometer resonance is about 15 kc/s).

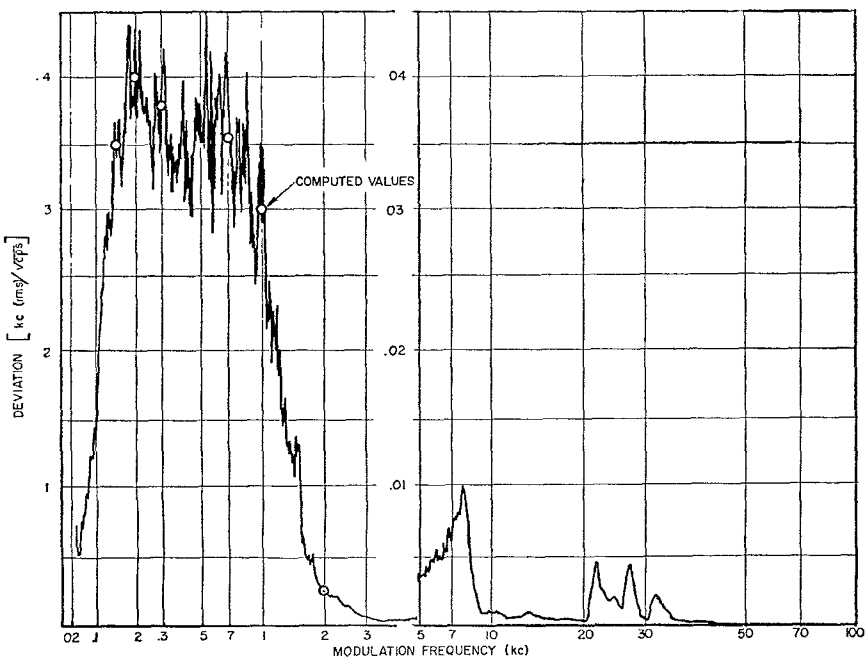

Fig. 4. Measured frequency modulation of a reflex klystron with the random vibration of Fig. 3.

Relative to Microwave Power Engineering

Recent erroneous reporting[1] of a facet of the proceedings of a microwave power engineering symposium has left the impression that microwave CW power transmission is limited, without qualification, by heating of the waveguide before the electric breakdown limit is reached. Consequently, a partial purpose of this correspondence is to show that microwave CW power transmission via re-entrant waveguide need not be limited by heat dissipation in the waveguide nor by electric breakdown even beyond the equivalent CW power capacity of high voltage (i.e., 132 to 750 kV) classical (i.e., 60 c/s) transmission lines. On the contrary, the feasibility of microwave power transmission is dependent on resolving the following.

1) The problems (e.g., spurious mode conversion, resonances, tolerances, etc.) associated with maintenance of the presently desired (e.g., circular electric) mode purity in sufficiently large oversized circular re-entrant waveguide so as to realize the required total (ohmic) attenuation and

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[1] For example, R. Henkel, "Believe power transmission via microwave now in sight," see, *Electronic News*, p. 28, April 19, 1965.

CW power carrying capacity comparable with that of high voltage classical transmissions lines.

2) Oversized waveguide component (e.g., bends, apertures, etc.) electric breakdown strength, with respect to that of the associated unobstructed oversized waveguide.

Another purpose of this correspondence is to compare tersely re-entrant waveguide and beam waveguide power transmission referred to in the subject reference. A final purpose is to make salient comparisons and suggestions regarding classical and microwave power transmission.

The amount of CW power that can be dissipated per unit length of re-entrant waveguide and open wire transmission line (or sheathed cable) depends upon their respective heat transfer capabilities. In particular, a one-meter diameter re-entrant circular waveguide propagating microwave energy at X band (i.e., 10 Gc/s) via only the circular electric (i.e., TE_{01}) mode and equivalent classical transmission line's (ohmic) attenuation (i.e., ~0.001 dB/km), is capable of safely carrying 2000 mW-CW at 30 kV/cm in normal air. Note that a 2000-kW-CW power capacity is at least comparable with that of a 400-kV two- (3-phase) circuit classical transmission line or that of eighteen 132-kV two- (3-phase) circuit classical transmission lines! Associated with this enormous power capacity of this waveguide is the *power dissipation* of that due to the (ohmic) attenuation, amounting to only 140 watts CW/ft. Assuming that the ambient air temperature is 70°F and the (copper) waveguide temperature at 120°F, the *power dissipation capacity* of this waveguide is about 2.5 kW/ft., even with no extended surface cooling. With optimum extended surface (i.e., spiral edge wound fin at a pitch of 2 or 3 fins per inch) cooling in ambient air at 70°F, the power dissipation capacity of this waveguide at 120°F rises to 12.5 kw-CW/ft.! Obviously, therefore, even for such re-entrant waveguide in 70°F ambient air and without extended surface cooling, there would be no CW power limitation due to undue temperature rise or heating of such waveguide.

Similarly with respect to electric breakdown in such re-entrant waveguide, it is erroneous to cite this as a limitation of CW power, since the potential CW power capabilities of such waveguide is beyond that capable with the highest existing and contemplated voltage classical transmission line.

In contrast, terrestrial microwave radiation beam power transmission over competitive distances (i.e., about 300 meters to about 10 miles), aside from being a lethal interception hazard at the necessary 25 watts/ft² power density, is confronted with high absorption of that energy in air; losses due to the difficulty in focusing the power in a sufficiently narrow beam to be conveniently received; enormous size antennas required at the frequency of relatively low absorption (i.e., 2 per cent per 10 miles at 1000 Mc/s) with reasonable focusing. For example, at this frequency a 110-ft diameter transmitter antenna and a 350-ft diameter receiver antenna 10 miles away would entail a 7 per cent loss of the transmitted energy, allowing for 2 per cent air absorption. When this is compared with 99 per cent utilization of the transmitted power at the classical power frequency, such microwave energy loss would not be competitively tolerable, to say the least.

To summarize these and other considerations in comparing microwave and classical power engineering, the following suggestions may be cited.

1) Power engineers at least desire power flow in both directions, capable of quick reversal, as dictated by system needs.
2) Cost need only be comparable with classical power systems, at least initially if no unusual advantages would accrue with microwave system substitution.
3) Comparable power generation, transmission and distribution capability is required.
4) Comparable (ohmic) attenuation of transmission is imperative.
5) DC must be converted to 60 c/s ac at distribution terminals, at least presently.
6) Classical dc transmission techniques are competitive with that of classical ac techniques only for distances of 350 to 450 miles and above. This would imply that microwave means would require longer distances to be competitive.
7) Efficiencies of generation and transmission must eventually be comparable to that of classical power means if it is to penetrate the latter fields of application.
8) The classical power engineer cannot accept higher (ohmic) losses, in general, than that which now prevails.
9) Use of higher voltages (i.e., 345–700 kV) reduces losses for the same kilowatts transmitted and capital cost per kilowatt, and so justifies reasons for using the higher voltages in contrast with microwaves.
10) No communication problems with respect to noise, phase, and delay distortion exist with microwave power generation, transmission, and rectification since only a single frequency is required.
11) Transmission of power via wires is limited by corona losses or insulation breakdown in the case of cables due to maximum tolerable electric gradient at the wire and across the dielectric. In the case of re-entrant waveguide, the maximum electric field need not be at the conductor and the electric field is also more uniformly distributed.
12) The power capacity of hollow oversize re-entrant circular waveguide, assuming negligible resonance and mode conversion loss, can be made to match that of the highest voltage (i.e., ~700 kV) classical transmission line.
13) Tolerance problems of waveguide transmission is not common to classical transmission lines.
14) There presently seems to be an apparent lack of indication towards solution of the problem of achieving the order of classical power efficiency (i.e., ~99 per cent) in microwave generation and rectification. This situation also prevails with respect to the problem of eliminating resonances and mode conversion losses in oversized re-entrant circular waveguides for microwave power transmission.
15) The oversized re-entrant waveguide of the size and for the frequency cited is extremely small compared with that of the classical transmission line (e.g., in the ratio of from 850:1 at 2000 mW-CW to 300:1 at 4000 mW-CW, in favor of the waveguide).
16) The relatively small grounded waveguide of from 2000- to 4000-mW-CW capacity can be submerged in the ground and hence accrue the associated advantages.
17) In a microwave power system the terminating loads must be matched to the system and utilize the full amount of coupled power while it is available. This restriction is predicated on the premise that no alternatives will evolve to circumvent it, which is indeed a conservative attitude.

Consequently, all things considered, it is unlikely that classical power engineering with respect to generation, transmission, and distribution will be obsolete in the forseeable future. But, this is not the cardinal point, in that the advent of generation of high power microwaves and transformation thereof to suitable form, directly (i.e., microwave motor[2]) or indirectly (i.e., rectification) with good overall efficiency will not only increase its applications with respect to possibly microwave power-from-the-ground-supported aerospace vehicles, but much more universally in what is considered the domain of classical power, including eventually the solutions of the problems associated with transmission of microwave energy in oversized re-entrant waveguide of comparable ohmic attenuation and CW power capacity of that of classical transmission lines. This would eventually offer the attractive prospect of using such waveguides as a grid system to transmit and distribute electricity on a very large scale in place of, or, as a supplement to classical power transmission. Although this alternative microwave system presents new problems and avoids some difficulties, it enables the power to be completely shielded in a controlled atmosphere and directed along the required route in a relatively small metal tube at earth potential.

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[2] Why not? At several milliwatts at S band (i.e., 3 Gc/s), several hundred Gauss magnetic components of the electromagnetic microwave field are realizable. Here reference is made to direct microwave motors, not the indirect (i.e., microwave to dc) type common in the literature.