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A TWT AMPLIFIER WITH A LINEAR POWER TRANSFER CHARACTERISTIC AND IMPROVED EFFICIENCY

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Abstract

A novel method to linearize the P_{out} versus P_{in} power transfer characteristic of TWTs by strictly internal modifications to the phase velocity of the slow wave circuit is described. The AM to AM characteristic approaches then that of a hard limiter and with a significantly improved intrinsic efficiency (1 to 2 dB) while the AM to PM conversion is not much different from that in an unmodified TWT, e.g. not exceeding 3°/dB. Work is in progress to develop techniques that will reduce this AM to PM conversion to smaller values. The theory of the "Dynamic Velocity Taper" (DVT) is introduced and applied to compute two different TWT's. The computed and measured power transfer characteristics of these two TWT's - one a Ku Band and the other a Ka Band TWT for broadcasting from space - are shown in their unmodified and modified form with their respective DVTs. The basic scheme of the DVT is the continueous and dynamic synchronization of the phase velocity on the TWT circuit with the conditions on the spent beam accomplished internally in the TWT.

A 4-minute movie contrasting the bunching phenomena in a TWT without and with a DVT will be shown.

An attempt is made to compare the advantages of an internal Velocity Taper - perhaps in combination with an external and simple phase linearizer-against active or passive predistortion techniques.

Theory of the Dynamic Velocity Taper

The idea and pursuit of a linear and distortion free amplifier is obviously not new. Until now, most attempts to eliminate or to reduce the nonlinearities in the AM to AM and AM to PM transfer characteristics were directed to techniques external to the TWTs by passive predistortion techniques or active feedbacks. A few cases were reported, without however much detail, about discretely placed positive and negative velocity tapers[1] such as to obtain improved intrinsic efficiencies associated with low distortions without achieving linearity. The method to be described in this paper addresses directly the problem of achieving internally a linear power transfer characteristic approaching that of an ideal hard limiter, together with an efficiency improvement by 1 to 2 dB. The resulting AM to PM conversion of about 30° can be accepted in some applications or be combined with a much simpler phase equalizer that provides an almost negligible phase shift. In addition, efforts are being made to develop new techniques that will retain the hard limiter characteristics with increased efficiency but reduce the total AM to PM conversion to small values.

To understand the technique it is useful and necessary to briefly review the small signal theory of TWT's, that Pierce developed and described with the help of several fundamental parameters listed below[2]:

$$C = \left(\frac{ZIo}{4Vo}\right)^{1/3} \text{ - gain and efficiency parameter}$$

$$b_o = \frac{u_o - v_o}{Cv_0} \text{ - velocity parameter}$$

u_o, v_o - initial electron and circuit phase velocities, respectively

$$b(z) = \frac{u - v(z)}{Cv(z)} \text{ - dynamic velocity parameter}$$

Observe that one dimensional theories, such as small signal theory of Pierce, use differently defined values for b, C, and Z from those used in multidimensional programs.

Consider now a typical AM to AM power transfer curve of a communication - type TWT such as the curves in fig. 1 marked w/o taper. The straight line region from origin up to about 6 to 10 dB below saturation covers a range of at least 25 dB of small signal gain. In this region a bunch has been formed and assumed a favorable phase location for production of power. However, in every small signal region both the amount of energy extraction and the velocity spread within the bunch are, by definition, negligible; the small signal gain is precisely predictable and corresponds directly to the velocity parameter b_o. As the small signal region ends the bunch begins to lose slowly energy to the wave. Looking at $b_o = \frac{(u_o - v_o)}{Cv_o}$ it may be seen readily that as u_o decreases b_o decreases too, the favorable synchronization between beam and wave deteriorates, the gain slope decreases more and more until saturation is reached. Another reason for this behavior is, of course, the development of an increasing velocity spread in the bunch. To prevent the small signal gain slope from falling we have to keep b_o constant.

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Obviously, since one cannot prevent u_0 from decreasing (we want the electrons to give up their energy), v must be decreased such as to keep b_0 approximately constant. We thus write

$$b(z) = \frac{u - v(z)}{Cv(z)} \quad (1)$$

This nonlinear TWT interaction Eq. (1) can be solved only with a modern high speed computer: As the internal conversion efficiency increases with distance, u decreases but this decrease is compensated by a reduction in $v(z)$. Mathematically, this is implemented by making b variable:

$$b(z) = b_0 + \alpha . \eta(z) = \frac{u - v(z)}{Cv(z)} \quad (2)$$

Since the electron velocity distribution as a function of energy extraction (distance) is known in the program we select the parameter α such as is necessary to maintain the gain linear by slowing the velocity $v(z)$ in a relation to the loss of energy or increase in efficiency. The computed and typical dependence of $\eta(z)$ on the location Z along the (unmodified) TWT with the input power as parameter is shown in Fig. 4. Were $\eta(z)$ a strickly exponential function of Z, as it is in the small signal region, we would obtain straight lines. Since the deviations from linearity are small, except at saturation, we are justified to put

$$\eta(z) \approx e^{r(Z-Z_0)} - 1 = r(Z - Z_0) + \frac{r^2(Z - Z_0)^2}{2!} + + \quad (3)$$

Z_0 is the value of z at which the intended taper is to begin. From Eq. (2) and (3) we can write

$$\frac{db(z)}{dz} = \alpha \frac{d\eta(z)}{dz} = \alpha r + \alpha r^2 (Z - Z_0) \quad + + \ . \ . \ . \quad (4)$$

And from Eq. (1) we get

$$\frac{db(z)}{dz} \approx - \frac{1 + Cb_0}{C} \cdot \frac{dv/dz}{v(z)} \approx \frac{1}{C} \frac{dv/dz}{v(z)} \quad (5)$$

Equating Eq. (4) and (5) and multiplying by dz

$$dz \alpha r C(Z - Z_0)\left[1 + \frac{r}{2} (Z - Z_0) + \frac{r^2}{3} (Z - Z_0)^2 + \ . \ . \ .\right] = - \frac{dv}{v} \quad (6)$$

The integration of Eq. (6) gives

$$v(z) = v_0 \exp - \left\{\alpha \ r C(Z - Z_0) \left[1 + \frac{r}{2}(Z - Z_0) + \frac{r^2}{3} (Z - Z_0)^2 + \ . \ . \ .\right]\right\} \quad (7)$$

with $v = v_0$ at $Z = Z_0$.

Now, in the nondispersive region of a helix or other periodic slow wave structures we may write, approximately

$$\frac{v}{c} \approx \frac{p}{2\pi a} \quad (8)$$

where c is the speed of light, p the pitch and a the helix radius.

From Eq. (7) and (8) it follows

$$p = p_0 \exp \left\{- \alpha r C(Z - Z_0) \left[1 + \frac{r}{2} (Z - Z_0) + \ . \ . \ .\right]\right\} \quad (9)$$

for $Z > Z_0$ and $p = p_0$ at $Z = Z_0$.

Approximately we get from Eq. (9) for $\alpha \, r C(Z - Z_0) << 1$

$$p = p_0 \left[1 - \alpha r C(Z - Z_0) - \alpha C \frac{r^2}{2} (Z - Z_0)^2 + \alpha^2 C^2 r^2 (Z - Z_0)^2 + - \ . \ . \ . \ .\right]$$

The taper should be placed after the small signal region, because too "early" a placement is distructive to the performance.

It is useful to calculate two other quantities of interest in designing tapers for linearized TWTs.

From Eq. (8) it follows directly for the local change in pitch

$$dp = \frac{2\pi a}{c} dv = - \frac{2\pi a}{c} Cv \ db = - \frac{v}{c} 2\pi a C \alpha d\eta = - p_0 C \alpha d\eta$$

The total change in the pitch is:

$$\Delta p = \int_{p_0}^{p_s} dp = - 2\pi a \frac{v_0}{c} C\alpha \int_{\eta(Zo)}^{\eta(Zs)} d\eta$$

$$= -2\pi a \frac{v}{c} C\alpha(\eta - \eta_0) \quad (10)$$

where saturation occurs at $Z = Z_s$

The number of turns in the tapered section is given by

$$N = \int_{Z_0}^{Z_s} \frac{dz}{p(z)} = \frac{1}{p_0} \int_{Z_0}^{Z_s} e^{\alpha C r(Z-Z_0)}\left[1 + \frac{r}{2}(Z-Z_0) + .\right] dz \quad (11)$$

and

$$N_0 = \frac{Z_s - Z_0}{p_0}$$

Obviously, $N - N_0$ is the difference in the number of turns

Discussion of Results

Figures 1, 2, and 5 show AM to AM and AM to PM transfer curves for the H8802 and H918 TWTs at 50 watts/12 GHz and at 75 W/20 GHz, respectively. For the unmodified and tapered TWTs measured curves are shown and compared with computed results on the H8802 experimental TWT built with a DVT. The existing discrepancy between the predicted and measured power for both cases - with and without the DVT - is largely due to the use of "cold" measured helix loss values for the computation of losses in the operational ("hot") TWT instead of actual, "hot" loss values. The latter are best determined by pulsed, low duty cycle RF power measurements against CW measurements. The heating up of the output section of helices causes appromixately 0.5 dB reduction in power output of 12 GHz.

Figure 3 shows the RF basic efficiency poltted versus the helix (cathode) voltage for the H8802 with and w/o the DVT. Note that higher voltage corresponds to higher beam velocity, higher b value and consequently higher power output. Note also that the TWT with DVT shows 16 percent efficiency - that is 5 p.c. points more than the TWT w/o DVT because higher efficiencies than in tubes w/o DVT are being achieved at lower voltages and lower b values, $b \approx o$, which produce smaller phase shift and a flatter, 0 slope gain response while the TWT w/o DVT shows a S.S. gain slope of 1.6 dB/GHz, as shown in Fig. 6. Note also that the improvement in efficiency that is due to the DVT is very significant and amounts at a given voltage to about 1.5 dB for the H8802 TWT. The degree of improvement depends, of course, on several design parameters.

The computed linearity of the AM to AM plots can be seen to approach the shape of a hard limiter. The AM to PM conversion is shown computed and measured for the H8802 only that was augmented with DVT. We know that, as may be expected, the helix with the DVT has a phase delay of about 30° but the total gain is also larger and the measured curves never exceed the 3.0°/dB slope. Another interesting point in this context is the question where to place the saturation on the curve approaching the flat top of a hard limiter. If that point were moved close to the knee the phase shift would become smaller.

At this time, a brief discussion of merits and disadvantages of predistortion techniques and/or active feedback alternatives to the velocity taper seems appropriate. Some points are obvious: the velocity taper, being an internal modification to the TWT, adds no weight or complexity, does not increase the cost and offers substantial bandwidth (> 10 percent) without any tuning. All properly designed negative velocity tapers (that is v(z) decreasing with distance), produce an efficiency improvement - an important benefit not available from any feedback system. In the case of a DVT a closely linear AM to AM characteristic may be obtained together with an improvement of 1 to 2 dB in efficiency. With an RF efficiency above 16 percent, a well designed multistage Depressed Collector (MDC) that has graphite, very low secondary emission electrodes, should raise the overall efficiency above the 50 percent level. A future replacement of BeO rods with Diamond 2A rods is likely to result in overall efficiencies around 65 percent since both losses are reduced and the impedance much increased.

Such improvements will make future TWTs as linear as Solid States Amplifiers but with an efficiency far above any present and potential ability of FETS.

Figures 7 and 8 shows the pitch variation in the DVT computed for the H8802 and H918 TWTS, respectively.

An expansion of the present method to include a simple passive phase cancellation devices, in addition to the DVT in the output section, is under study at Hughes EDD. Some results of this work may be available for the March AIAA presentation.

A 4-minute movie that visualizes the bunching phenomena in untapered TWT's and in those having a DVT will be shown.

References

1. Collomb, J., Gosset, P., and Raye, H.: "A New Generation of Satellite Traveling-Wave Tubes for TV-Broadcasting and Telecommunications," AIAA Paper 80-0485, April 1980.

2. Pierce, J.R., Traveling Wave Tubes, Van Nostrand, New York, 1950.

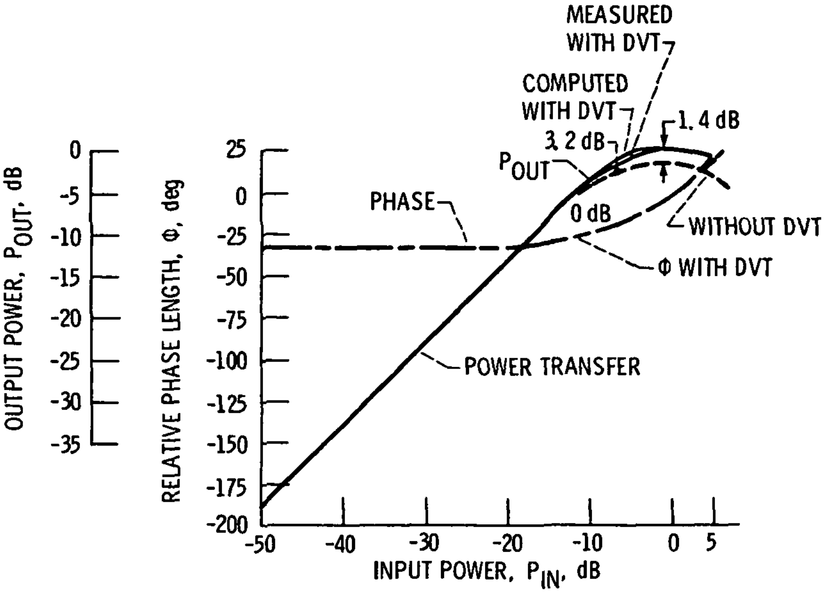

Figure 1. - Hughes 8802 experimental 12 GHz TWT. AM/AM and AM/PM conversion on a double decibel scale with and without DVT.

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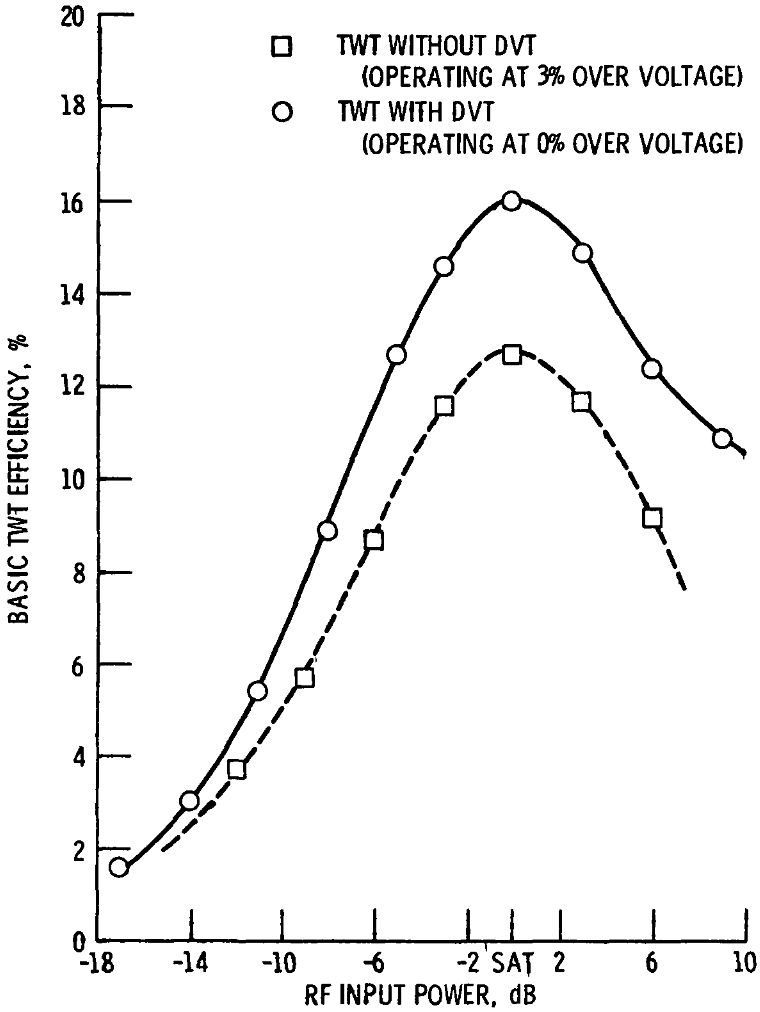

Figure 2. - Basic efficiency measured versus power input with and without DVT, for the Hughes 8802.

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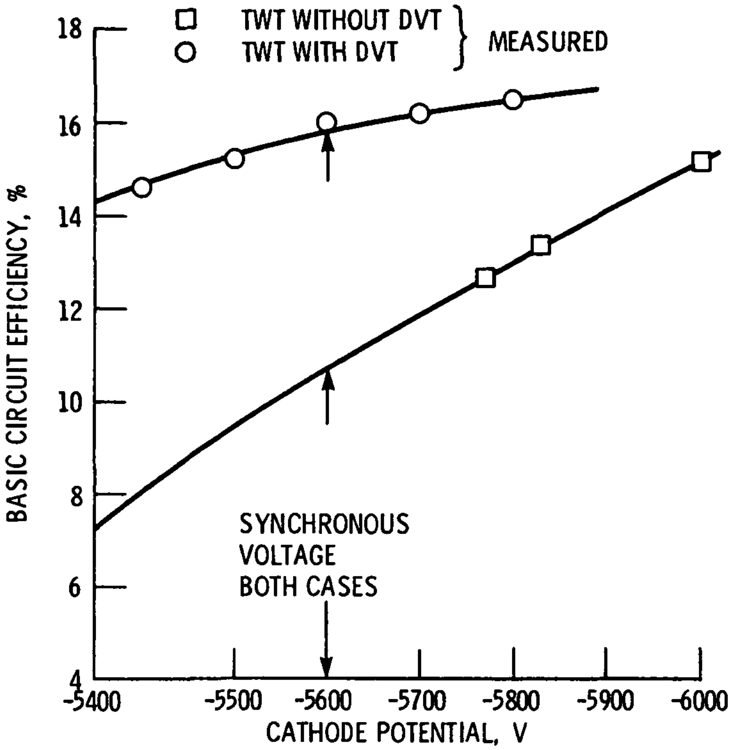

Figure 3. - Basic efficiency versus voltage with and without DVT for the Hughes 8802, measured.

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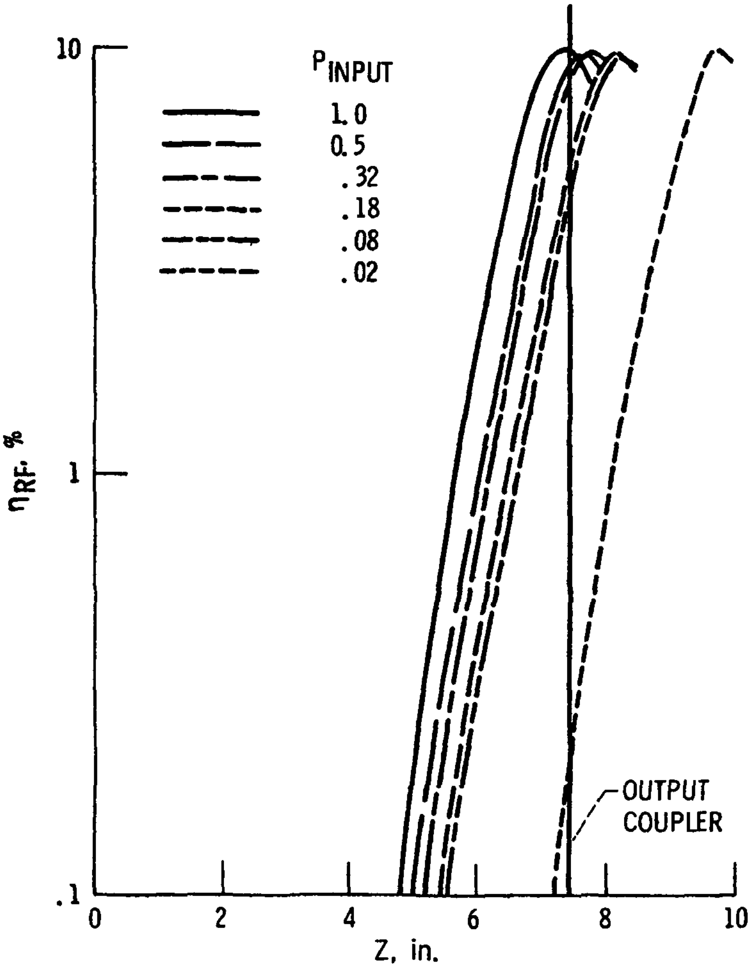

Figure 4. - Basic efficiency versus distance along the helix with power input as parameter.

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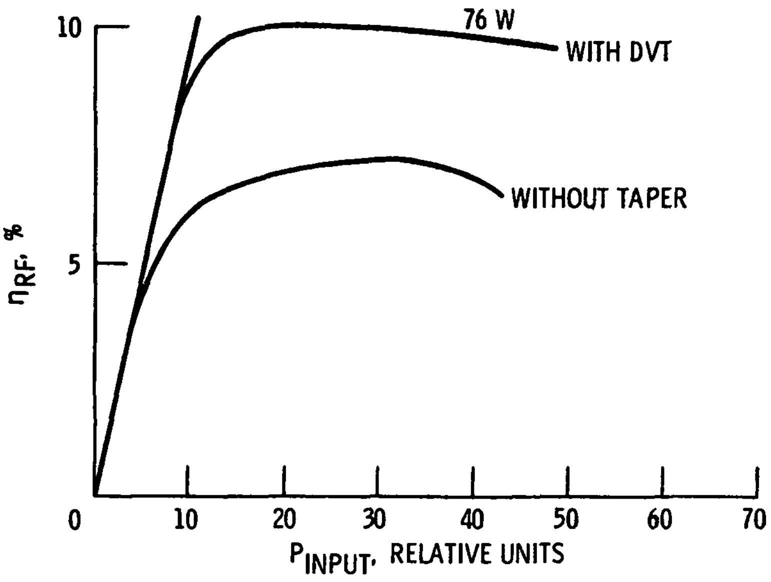

Figure 5. - Power transfer characteristic for the Hughes 918 with and without the DVT. (Computed.)

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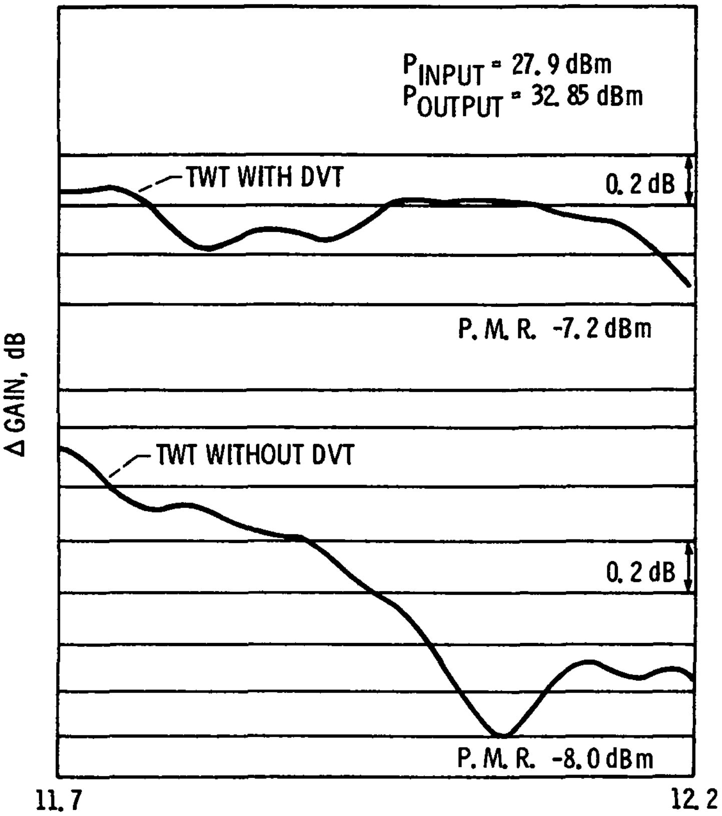

Figure 6. - Gain variation for the Hughes 8802 with and without the DVT. (Measured.)

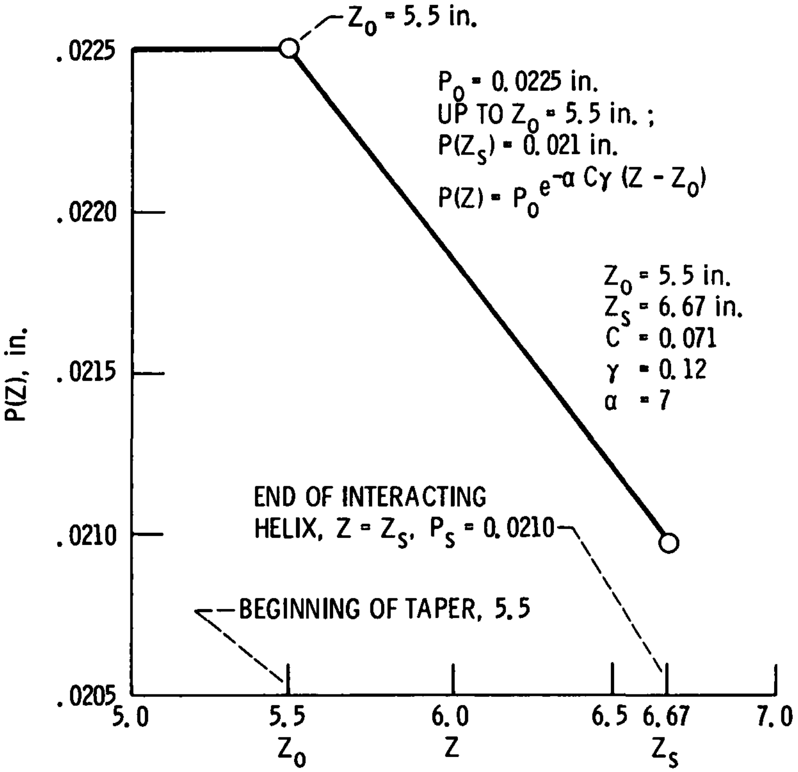

Figure 7. - Pitch variation in the DVT for the Hughes 8802.

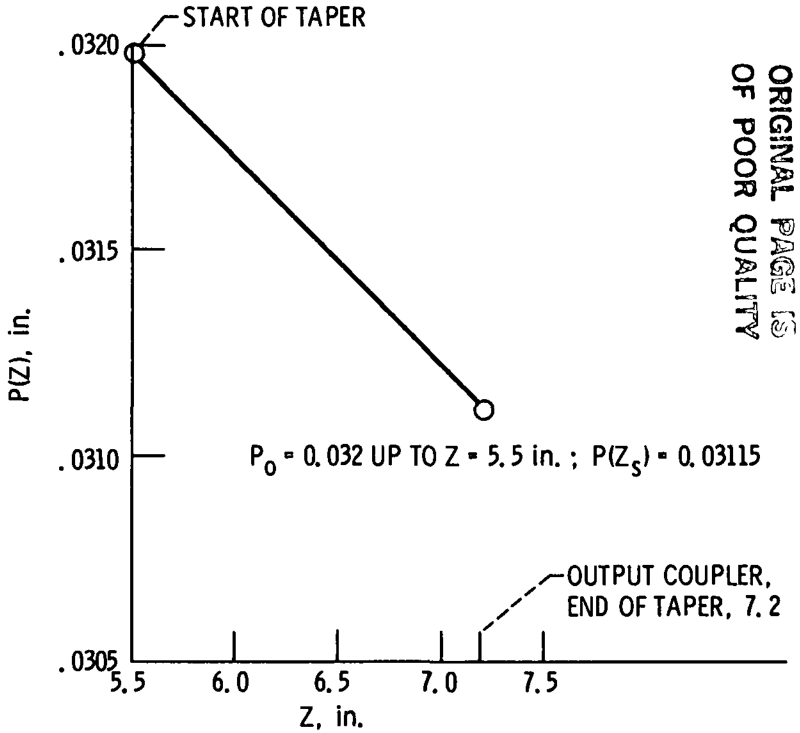

Figure 8. - Pitch variation in the DVT for the Hughes 918.

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15 Supplementary Notes

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16 Abstract

A novel method called "Dynamic Velocity Taper" to linearize the P_{out} versus P_{in} transfer characteristic that does not require any extraneous circuitry or tuning, has large bandwidth capabilities (> 10 percent) and offers also an increase in the intrinsic TWT efficiency by 1 to 2 dB is described. In addition, the method permits the TWT to be operated at or near the synchronous voltage ($b \simeq o$) which produces a flat small and large signal gain responses and low AM to PM conversion. The physics of the method and experimental verification are given. The implementation should have a significant impact on TWT performance and increase the channel capacity of communication satellites.

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