Mechanical Load Cell Based on Cavity-Controlled Microwave Oscillators

Francis J. M. Farley, Jagdish K. Vij, Antoni Kocot, U. M. S. Murthy, and Michael Burgess

***Abstract*—A novel device consisting of a rectangular resonator to which two oscillators are coupled at right angles to each other is described. The frequency of each oscillator is controlled by the cavity, and distortions caused by mechanical load change the two frequencies in opposite directions. The detector which is arranged at an angle of 45° to the probes of the two oscillators picks up a beat signal whose frequency in the MHz range is linearly related to the mechanical load applied across the cavity. The oscillators using GaAs MESFET's have been designed to detect small distortions in the cavities caused by a mechanical load.**

I. Introduction

During the last decade microwave power sources using GaAs FET's have offered an attractive alternative to the use of klystrons and Gunn diode devices. This has been made possible because of their moderate but sufficient power capabilities owing to their high efficiency. But it is also due to the ease in the design and a miniaturization of the microwave systems for which the oscillator forms a part. The design of an oscillator which is stabilized in frequency by a dielectric resonator is quite common [1], [2]. However, a design based on cavity-controlled stabilization is much more difficult. An analysis of the probe-coupled oscillator has been carried out by Materka and Mizushima [3] and also by Madihian *et al.* [4] and these concepts have been used to construct a device.

We describe a cavity resonator coupled to one or two oscillators. A suitable resonator shape has been suggested and calculations for a change in its frequency with mechanical distortion are given. A novel device [5], where two oscillators at right angles to each other are coupled to a resonator cavity, is described. The resulting signal picked up by a probe placed at an angle of 45° to these oscillators is a beat frequency signal. The frequency of the beat signal is found to be linearly related to the mechanical load applied to the cell. The frequency can be measured directly using either an ordinary frequency meter or a voltage-to-frequency converter. The device can be employed as a transducer for detecting small distortions in the cavities caused by a load.

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II. Theoretical Aspects of the Resonator-Controlled Oscillator

The theoretical aspects of the magnetic coupling between the resonator and the matched active microstrip line are discussed by Abe *et al.* [2]. When a resonant circuit is placed at a distance of $n\lambda_g/2$ from the negative conductance of the device which is coupled to a matched terminated line, the oscillation frequency near the resonance can be expressed by an equation:

$$\frac{f_0 - f}{f_r} = \frac{f - f_r}{f_r}\left(1 + \frac{\beta}{(1+\beta)^2}\frac{Q_r}{Q_0}\cdot\frac{1}{1+\left(\dfrac{2Q_r}{1+\beta}\cdot\dfrac{f-f_r}{f_r}\right)^2}\right) \tag{1}$$

where f_0 and Q_0 are the frequency and Q value of unstabilized oscillator; f_r and Q_r are the resonance frequency and Q value of the cavity; f is the resulting oscillation frequency; β is oscillator to cavity coupling factor; and λ_g is the wavelength of the wave in the stripline. The results of this analysis show that the frequency of the oscillator is not completely governed by the cavity but the latter's frequency can be controlled within a certain frequency range Δf. Fig. 1(a) shows the dependence of the oscillation frequency (f) on the resonance frequency of the resonator (f_r) for different values of Q_0 and for typical values of Q_r and β. The figure shows that f varies almost linearly with f_r over a certain range of the latter. The difference in the high and low frequencies which mark the end of this linear range is the frequency range Δf mentioned above. This range is dependent on Q_0, Q_r, and β. An expression for Δf for the case $Q_r \gg Q_0$ can be quite easily derived; Δf is approximated as

$$\Delta f \cong 2f_r\sqrt{\frac{\beta}{Q_0 Q_r}}. \tag{2}$$

On differentiating both sides of (1), and on the assumption that $f \cong f_0 \cong f_r$, we obtain an expression for a change

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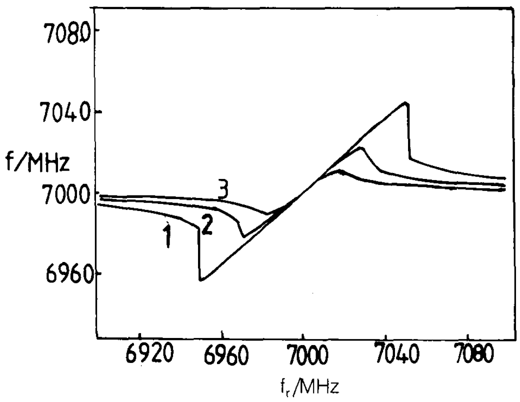

Fig. 1. Dependence of the oscillation frequency on the resonant frequency of the cavity for different Q_0: (1) 20, (2), 40, (3) 80. $\beta = 1$. $Q_r = 1000$.

in the oscillation frequency, f, with respect to the resonant frequency, f_r, of the cavity:

$$\left(\frac{\partial f}{\partial f_r}\right) = \left(1 + \frac{(1+\beta)^2}{\beta}\frac{Q_0}{Q_r}\right)^{-1}. \tag{3}$$

For $Q_r \gg Q_0$, $(\partial f/\partial f_r)$ is found from (3) to be close to unity, but for typical values of Q_r, Q_0, and β, $(\partial f/\partial f_r)$ is somewhat less than unity. On the other hand, as Q_r goes to infinity, Δf becomes very small, and this will limit the range over which the cavity can control the frequency. The typical values of the various parameters are $Q_r = 2000$, $Q_0 = 100$, and $\beta = 1$, which give rise to $\Delta f \cong 31$ MHz and $\partial f/\partial f_r \cong 0.8$. It may be noted that $(\partial f/\partial f_r)$ refers to the slope of the curve, which shows a change in the oscillation frequency with the resonant frequency of the cavity provided the cavity can control the oscillations. The quantity Δf is the range of this frequency control. Equation (3) is valid for the case $f \cong f_0 \cong f_r$.

III. Cavity Perturbations

A cavity of square cross section has been designed to achieve two perpendicular modes: H_{101} and H_{011}. These correspond to (a) the electric field parallel to the y axis and the magnetic field in the x–z plane (Fig. 2), and (b) the electric field parallel to the x axis and magnetic field in the y–z plane. Since the dimensions along the y and x axes are equal, the two frequencies f_{H101} and f_{H011} are equal.

For the resonator constructed from brass and for a frequency of 7 GHz, the skin depth [6] is calculated to be $\delta = 0.0015$ mm, giving $Q = 5060$.

For a cavity at resonance the average magnetic and electric energies stored in the cavity are known to be equal. If a small perturbation is made in the dimensions of the cavity by shifting one of the cavity walls, a change in one type of energy would occur more than the other, and the resonant frequency would then shift by an amount necessary to equalize these energies. When a small volume, ΔV, is removed from the cavity by altering its boundaries, the frequency shift is given by [7]

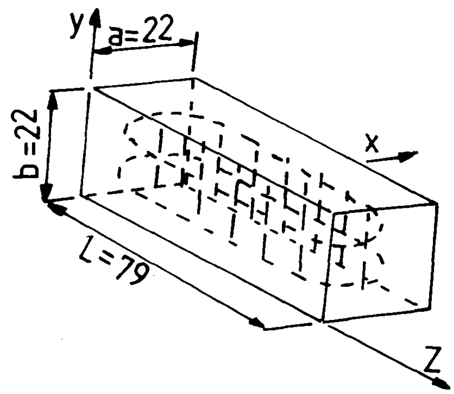

Fig. 2. Cavity resonator with H_{101} modes.

$$\frac{\Delta f}{f} = \frac{\int_{\Delta V}(\mu H^2 - \epsilon E^2)\,dV}{\int_V(\mu H^2 + \epsilon E^2)\,dV} = \frac{\Delta U_H - \Delta U_E}{U} \tag{4}$$

where ΔU_H and ΔU_E are the magnetic and the electric energies removed from the cavity, respectively, and U is the total stored energy. The energies are all considered to be time averages.

The total energy stored in the resonator can be calculated from the electric field at the instant when it is at its maximum, and the two magnetic field components at that instant are zero. Hence

$$\begin{aligned} U &= \frac{\epsilon_0}{2}\int\int\int E_y^2\,dx\,dy\,dz \\ U &= \frac{\epsilon_0}{2}\int_0^l\int_0^b\int_0^a E_0^2 \sin^2\left(\frac{\pi x}{a}\right)\sin^2\left(\frac{\pi z}{1}\right)dx\,dy\,dz \\ &= \frac{\epsilon_0}{8}E_0^2\,abl. \end{aligned} \tag{5}$$

The next step is to calculate the change in frequency of the H_{101} mode when one of the side faces of the resonator is deflected. Since the electric field is zero at the side faces, i.e., for $x = 0$ and $x = a$, this means that only the magnetic field energy is affected, i.e.,

$$\Delta U_E = 0 \tag{6}$$

$$\begin{aligned} \Delta U_H &= \mu\int_{\Delta V}(H_z^2 + H_x^2)\,dV \\ &= -\epsilon_0 E_0^2\,\Delta V \end{aligned} \tag{7}$$

where ΔV is the volume removed from the cavity, and $\epsilon_0 E_0^2$ is the magnetic energy density at the sidewall. The standard field equations for the modes are used.

Next we assume, that the deflection of the $y-z$ sidewall is pyramidal in shape, with its base restricted to that of a square cross section; its dimensions are such that the diagonal of the square is assumed to be equal to the height or the width of the cavity. Since the load is applied at the center of this sidewall, the center of the square must coincide with it. This is a reasonable assumption for a cavity with $l \gg a = b$. We estimate that the change in volume, ΔV, is roughly equal to

$$\Delta V = \frac{\Delta a . b^2}{6}, \qquad a = b \tag{8}$$

where Δa is the amplitude of maximum deflection of the $y-z$ sidewall at the point of the load. If the opposite sidewall is point supported exactly opposite to the point of application of the load, then (8) needs to be multiplied by a factor of 2. Using (4), (7), and (8), we obtain an expression for the fractional change in the frequency for the H_{101} mode:

$$\frac{\Delta f_1}{f_1} = +\frac{4}{3}\frac{\Delta a}{l}. \tag{9}$$

It can be proved from (4) that a distortion in the set of walls in the $y-z$ plane causes a negligible change in the frequency of the H_{011} mode. However, the load also produces a distortion Δb in the perpendicular set of walls (in the $x-z$ plane), which produces a change predominantly in the frequency of the H_{011} mode while not significantly affecting the frequency of the H_{101} mode.

Let Δb be the amplitude of maximum deflection of the $x-z$ face corresponding to the distortion Δa of the $y-z$ face. Then the equation for the fractional variation in the frequency of the H_{011} mode can be written as

$$\frac{\Delta f_2}{f_2} = -\frac{4}{3}\frac{\Delta b}{l}. \tag{10}$$

For $f_1 \approx f_2 \approx f$, we find that

$$\frac{\Delta f_1 - \Delta f_2}{f} = \frac{4}{3}\frac{1}{l}(\Delta a + \Delta b) \tag{11}$$

where Δa and Δb are linearly related to each other and to the load.

IV. Design of the System

A. Description of the Oscillator

Fig. 3(a) shows an oscillator with a resonant cavity, and Fig. 3(b) its equivalent circuit. An electrical probe is used to couple the oscillator to the resonator. The output of the resonator is magnetically coupled to the detector. In the equivalent circuit, X_p is the probe reactance, and the ideal input transformer $(n_1 : 1)$ represents the probe coupling while the ideal transformer $(n_2 : 1)$ represents the inductive output coupling.

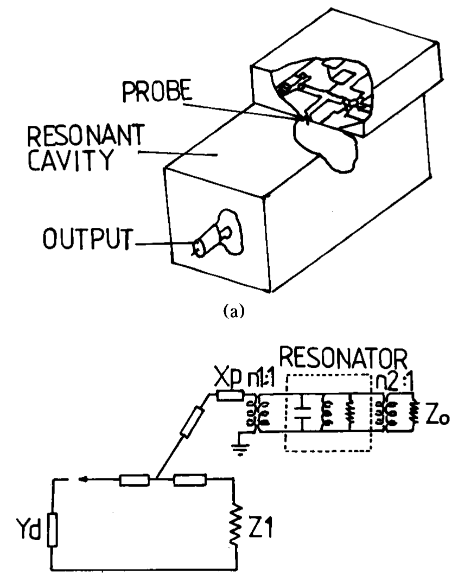

Fig. 3. (a) View of the cavity resonator controlled oscillator. (b) Its equivalent circuit.

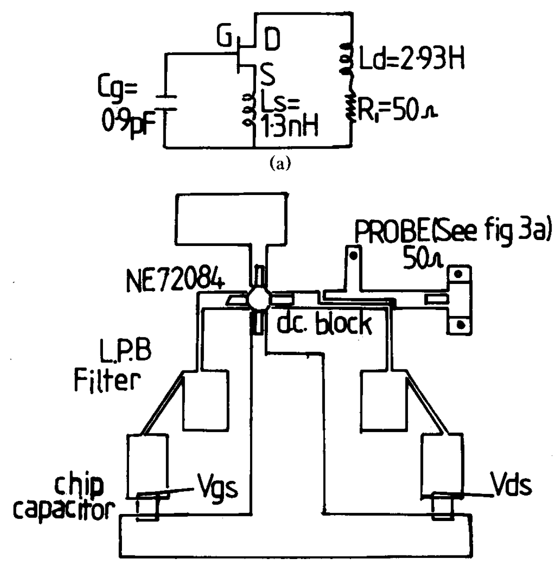

Fig. 4. (a) Topology of the oscillator. (b) Its microstrip realization.

B. The Oscillator Realization

The topology of the oscillator (Fig. 4(a)) is chosen with a series feedback element. It is one of the topologies suggested by Johnson [8]. The oscillator is terminated in a matched load of 50 Ω for improving its frequency stability. The design is based on small-signal S parameters for the MESFET NE72084 for the following bias conditions: $V_{DS} = 3$ V, $V_{GS} = -1.5$ V, and $I_D = 30$ mA.

The microstrip circuit, shown in Fig. 4(b), is fabricated on Duroid substrate with a thickness of 0.502 mm (0.02 in.). The matching inductance, L_D, is realized as a stub at the drain stripline. The oscillator is coupled to the resonator of dimensions $a = b = 22$ mm and $l = 79$ mm. The

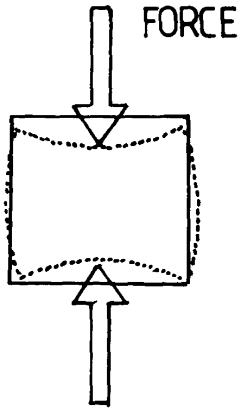

Fig. 5. View of the cavity cross section under a load.

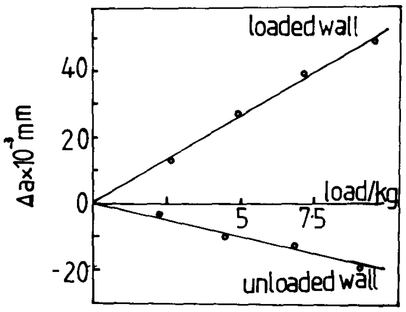

Fig. 6. Measured mechanical distortions as a function of load.

TABLE I
COMPARISON BETWEEN THE MEASURED AND THE CALCULATED MECHANICAL DISTORTION

Cavity Distortion	Calculated	Measured
$\frac{\Delta a}{\Delta L}$ $\frac{\text{mm}}{\text{kg}}$ Loaded wall	4.6×10^{-3}	3.4×10^{-3}
Unloaded wall	1.7×10^{-3}	2.1×10^{-3}

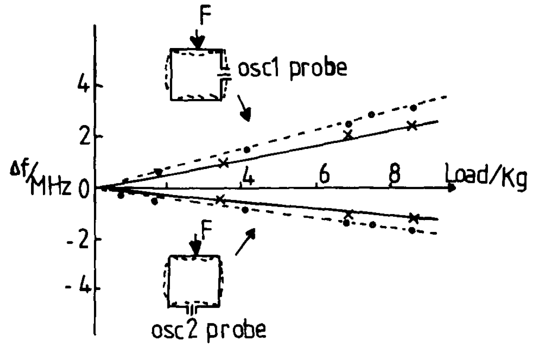

Fig. 7. Cavity resonant frequency and the cavity controlled oscillation frequency as a function of load: --∘- cavity resonance frequency; —oscillation frequency. $V_{DS} = 4$ V; $V_{GS} = -2$ V.

coupling probe is placed at the end of the drain stub and goes into the cavity via a circular aperture in one of its rectangular walls (see Fig. 3(a)). The output signal is picked up by the loop placed in the center of one of the end square plates. The Q value of the resonator was measured to be 4840, in comparison with the calculated value of 5060.

The oscillator frequency as well as the resonant frequency of the cavity decreases with an increase in probe length. The former increases at a higher rate with the probe length than the latter. This follows from the fact that the probe constitutes an extension to the stripline and it provides an additional reactance, X_p (Fig. 3(b)), for the matching circuit. Having fabricated the circuit, the performance of the oscillator with different bias conditions was tested. We find from this study that the frequency stability of the cavity-controlled oscillator with respect to V_{DS} is extremely high. The frequency of the oscillator can be altered by varying V_{GS}. It is found that the frequency varies linearly with the bias voltage; this can be used for frequency tuning purposes.

The power level at the drain is measured to be 20 mW. The efficiency at the drain output is found to be 22%. The power at the cavity output, which is dependent on the output coupling, can be varied between the levels of 0 and 5 mW. The accuracy in measuring the frequency of oscillation of the cavity coupled oscillator using a spectrum analyzer (which depends on the resolution of the spectrum analyser) has been found to be better than 1 kHz.

V. Results for the Mechanical Distortion of the Cavity

The cavity was mechanically loaded at two points situated in the middle of the opposite walls shown in Fig. 5. The force applied to the walls shifts these toward the center of the cavity and the two unloaded walls bulge out as shown in this figure. The maximum mechanical distortions of the cavity walls under stress were calculated for a load of up to 10 kg. The simplified technique used to estimate these elastic distortions [9] involved interpolating between known upper and lower bounds for simply supported and fully clamped plates with an appropriate aspect ratio [10]. The degree of interpolation was based on the distortion of an analogous skeletal frame of the box cross section, which was evaluated using a stiffness method approach. Axial shortening of the bulging box walls was negligible, and other second-order effects were not considered. The results for the measured deflection shown in Fig. 6 are found to be in good agreement with those calculated using the numerical approach described above (see Table I).

As a consequence of the wall's distortion in shape, a variation in the resonant frequency of the cavity can be observed. Fig. 7 shows a resonance frequency variations for the H_{101} modes and H_{011} under the varying load. These depend on the position of the probe in relation to

TABLE II
COMPARISON BETWEEN THE FREQUENCY SHIFTS OF THE CAVITY AND THE OSCILLATOR WITH MECHANICAL LOAD (L)

		Measured	Calculated
Cavity resonance frequency shift $\frac{\Delta f_r \text{ MHz}}{\Delta L \text{ kg}}$	Probe 1	0.36	0.5
	Probe 2	-0.20	-0.2
Oscillator frequency shift $\frac{\Delta f \text{ MHz}}{\Delta L \text{ kg}}$	Oscillator 1	0.29	0.4
	Oscillator 2	-0.15	-0.16

the load axis (Table II). On using results of Δa per kg of the load from Table I and $f = 7$ GHz, we can estimate $\Delta f_1 = 0.5$ MHz/kg for the set of concaved walls and, for the opposite set of convexed walls, $\Delta f_2 = -0.2$ MHz/kg. Table II shows a comparison between the frequency shifts of the cavity $(\partial f_r/\partial L)$ and the oscillator $(\partial f/\partial L)$ with mechanical load.

We observe a similar behavior for the two oscillators in their respective probe positions (insets Fig. 7) in terms of the variation of their frequencies under load. We find that $\Delta f/\Delta L$ is less than $\Delta f_r/\Delta L$ for the reason that $\partial f/\partial f_r < 1$. This follows from $\partial f/\partial L = \partial f/\partial f_r \cdot \partial f_r/\partial L$; $\partial f/\partial f_r$ is calculated from (3) and the value is found to be 0.8 for $Q_r = 2000$, $Q_0 = 100$, and $\beta = 1$.

VI. MECHANICAL LOAD CELL

To measure mechanical loads via the distortion of the cavity, the change of frequency could be compared with some stable reference, and the cavity would have to be free of drifts, for example, those caused by temperature. A better technique is to excite the cavity simultaneously in the two orthogonal modes, one of which increases in frequency under mechanical loading while the other decreases. The beat frequency will then be a measure of the load. This avoids the need for a separate reference oscillator, and environmental drifts are likely to be similar in the two systems and will therefore largely cancel out. This has been provided by measurements; a change in temperature of the cavity by 15° C does not produce any observable frequency drifts.

In order to measure the difference frequency, Δf, we used two oscillators with probes placed on the two walls perpendicular to each other (Fig. 8). The output loop is fixed at an angle of 45° to the axes of the oscillator probes. This was done in order to obtain signals equal in amplitude from the two oscillators. The difference frequency as a function of the load is measured by a back diode detector (Omni-spectra).

We have assumed that the two oscillators are uncoupled to each other and have calculated the alteration in the their natural frequencies. Very probably, however, there will be some coupling between the two oscillators, and this will change the frequencies. This is in close analogy with two LC circuits tuned to the same frequency; when they are coupled the resonance splits into two peaks. The analysis of two coupled oscillators can be carried out to show that to have a useful load cell working

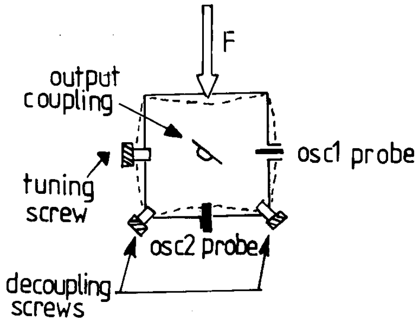

Fig. 8. A device for measuring the beat frequency as a function of load.

in the linear region, it is desirable to have

a) low coupling between the two oscillators;
b) an initial offset, so that $f_1 \neq f_2$.

The problem of decoupling the two oscillators from each other is detailed in [11]. In principle the coupling between the two oscillators can be varied by introducing small screws projecting into the cavity. The screw must be positioned where there is an electric field component from each mode. Then radiation from the screw will couple the modes. The phase of the coupling depends on the screw position, so with two screws positioned as in Fig. 8 one can in principle tune out any coupling. We could set the initial difference frequency, Δf_0, for the undistorted resonator in order to reduce the coupling between the two oscillators. This can be done by choosing slightly different probe lengths for the two oscillators and then finely adjusting Δf_0 by using tuning screws (shown in Fig. 8). This can also be done by varying V_{GS} for a single oscillator.

For Δf_0 extending down to 1 MHz, we can observe a beat frequency signal of amplitude 60 mV. The signal is observed to be sinusoidal. In practice, however, it is better to set the initial beat frequency value, Δf_0, for zero load, higher than 1 MHz. The beat frequency was found to be a linear function of the load in the range mentioned above. The frequency is found to be equal (within measurement error) to the difference between the frequencies for the two oscillators shown in Table II and is also found to agree reasonably with that calculated using (11). The error in measuring the beat frequency was less than 0.3 kHz and is due mainly to the frequency instability of the oscillators mentioned in Section IV.

VII. CONCLUSIONS

Oscillators using NE 72084 GaAs FET's have been designed with a high frequency stability. The frequency of oscillation is controlled by the cavity resonator. The system has been used to determine distortions in the shape of the resonator produced by a load. We find a linear dependence of the oscillation frequency on the load. With the two oscillator probes mounted at right angles and coupled to a resonator cavity, the beat frequency is also found to be a linear function of the load, and is equal to the difference between the frequencies of the two oscillators, with their probes in their respective positions.

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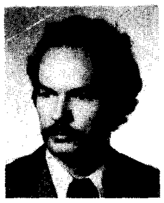

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