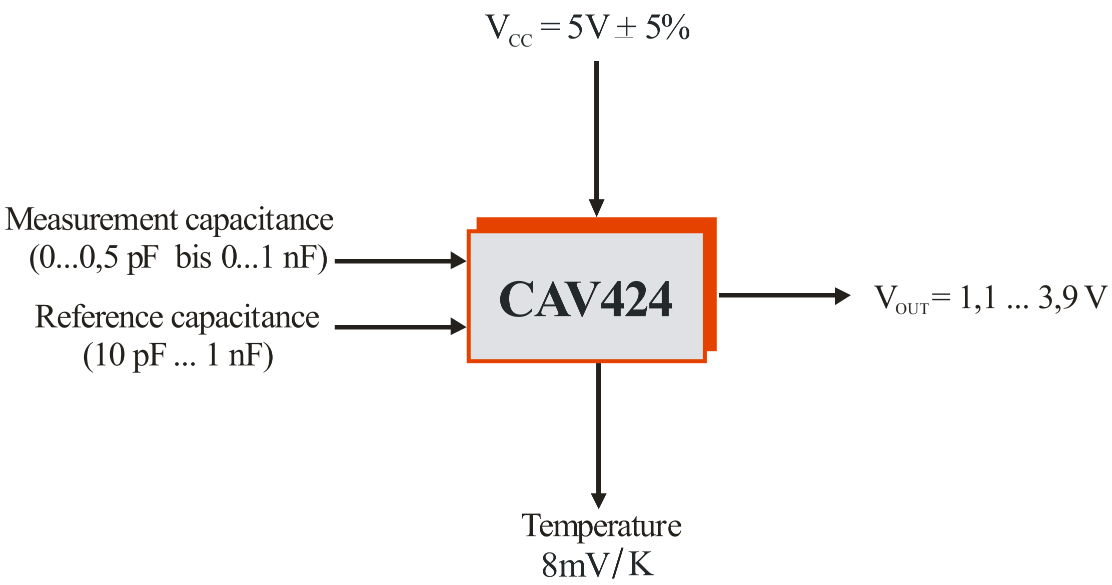
# CAV424 - C/U transducer IC with adjustable output voltage

## PRINCIPLE FUNCTION

**Capacitance/Voltage converter IC with an adjustable, differential output, integrated temperature sensor**




## Typical applications

CAV424 is an analog linear transducer. The IC is suitable for all capacitive measurements which require a voltage output signal which is proportional to the change in the capacitance to be measured. It can be used for:

- **Distance measurement**
- **Pressure sensing**
- **Humidity measurement**
- **Level sensing**
- **Measurement of strength**
- **As a capacity input circuit for microprocessors or as a stand-alone device**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## FEATURES

- High detection sensitivity
- Wide capacitor measuring range: 5% – 100% relative to the reference capacitor, 0.5pF to 1nF.
- Detection frequency of up to 2kHz
- Adjustable output offset
- Adjustable full scale output signal
- Differential output
- High voltage immunity
- Temperature output signal
- Wide temperature range: -40°C...+105°C
- Supply voltage: 5V ± 5%
- Ratiometric output voltage
- Simple calibration (Excel program)
- RoHS compliant

## GENERAL DESCRIPTION

CAV424 is an integrated C/V converter circuit which contains full signal conditioning electronics for almost any source of capacitive signal. For measurement capacitor $C_M$ CAV424 detects the relative change in capacitance $\Delta C_M = C_{M,max} - C_{M,min}$ in relation to that of a given, fixed reference capacitor $C_R$.

The IC has been optimized for reference capacitors of between 10pF and 1nF where the change in capacitance $\Delta C_M$ can be 5% to 100% of the basic capacitance $C_{M,min}$.

The differential voltage output has been specially designed for connection to an A/D converter. Together with the integrated temperature sensor and a processor calibratable systems can be assembled. A simple Excel program simplifies the dimensioning of CAV424.

## BLOCK DIAGRAMM

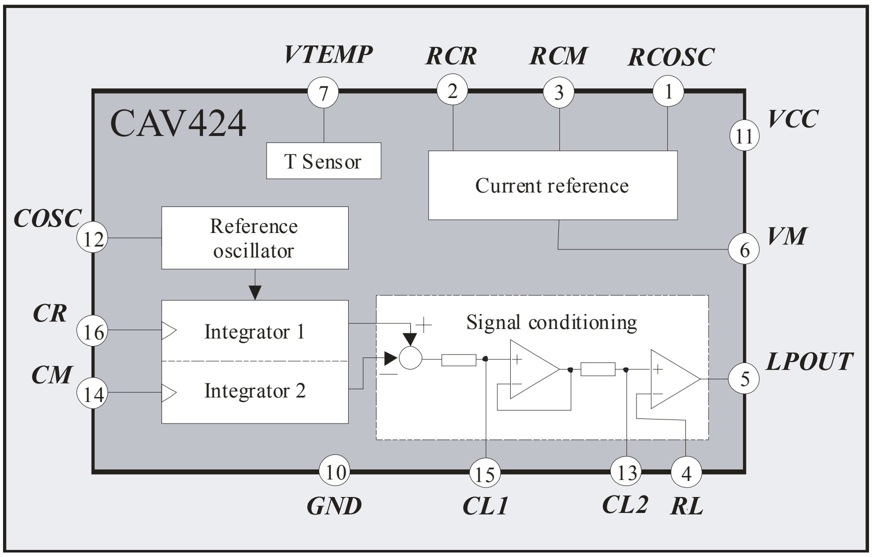
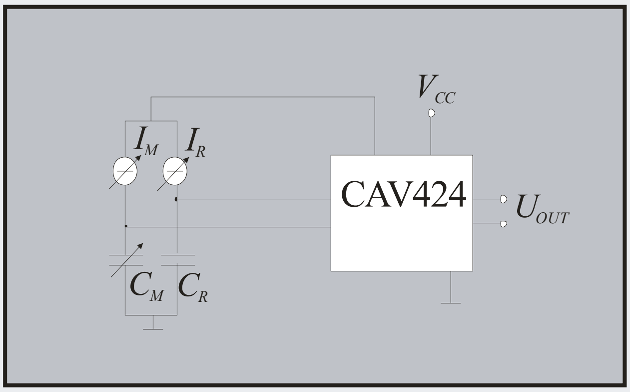



*Figure 1*: Block diagram CAV424

## PRINCIPLE OF MEASUREMENT

CAV424 is an integrated C/U converter circuit which contains full signal conditioning electronics for capacitive signal sources.




Current sources $I_M$ and $I_R$ are integrated in CAV424

***Figure 2:*** **Principle of capacitance measurement using CAV424**

The principle of measurement with the CAV424 entails recording a change in capacitance in a sensor bridge comprising two adjustable current sources and two capacitors, the measurement capacitance ($C_M$) of which can be altered by the amount $\Delta C_M = C_{M,max} - C_{M,min}$. The second capacitor is defined as a reference ($C_R$, see *Figure 2*). $C_{M,min}$ is the basic capacitance of $C_M$. The change in measurement capacitance is compared to the fixed reference capacitance $C_R$ and the resulting signal converted into an output voltage signal.

## HOW CAV424 WORKS

The CAV424 IC functions according to the following principle. An adjustable oscillator, the frequency of which is set using capacitor $C_{OSC}$, drives two symmetrical integrators which are phase-locked and clock-synchronized (see *Figure 3*). The amplitudes of the two driven integrators are determined by capacitors $C_R$ and $C_M$. With high common-mode rejection and a high resolution, the difference between the two amplitudes produces a signal which corresponds to the difference in capacitance between $C_R$ and $C_M$ (rectifier effect). This difference signal is then filtered in an ensuing active low pass. The resulting voltage signal passes on to an adjustable amplifier stage which sets the output signal to the required value.

If capacitors $C_M$ and $C_R$ are the same, following rectification and filtering (see *Figure 5*) a DC-voltage signal is generated with a value of 0. Should $C_M$ change (measurement capacitor), a DC-voltage signal is produced which is proportional to $\Delta C_M$.

If $C_M$ and $C_R$ are not the same, when $\Delta C_M = 0$ an offset would be generated at the output which is superimposed onto the actual direct voltage signal.

## Oscillator function

The integrated oscillator charges up and then discharges the external oscillator capacitor $C_{OSC}$ (see *Figure 3*).

The oscillator current $I_{OSC}$ is determined by external resistor $R_{OSC}$ and reference voltage $V_M$:

$$I_{OSC} = \frac{V_M}{R_{OSC}} \qquad (1)$$

The oscillator frequency $f_{OSC}$ is calculated as:

$$f_{OSC} = \frac{I_{OSC}}{2 \cdot \Delta V_{OSC} \cdot C_{OSC}} \qquad (2)$$

where $\Delta V_{OSC}$ is the difference between the thresholds of the internal oscillator ($V_{OSC,HIGH}$ and $V_{OSC,LOW}$). $\Delta V_{OSC}$ is defined via internal resistors in the IC and has a value of 2.1V @ $V_{CC} = 5$V (see *Figure 3*). The oscillator frequency can thus be specified by the choice of $R_{OSC}$ and $C_{OSC}$; the relevant maximum and minimum values are given in *Table 1*.

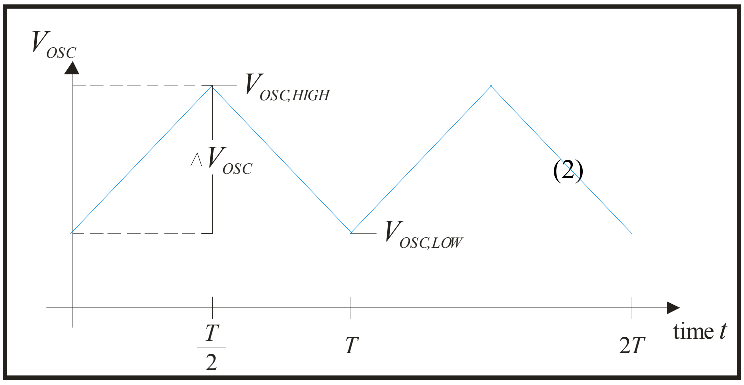



***Figure 3:*** **Oscillator voltage curve**

## Capacitive integrators

The built-in capacitive integrators function works in the same way as the oscillator. One difference lies in the discharge time, which here is half the length of the charge-up period. Furthermore, the minimum oscillator voltage for the integrators is internally clamped to a value of $V_{CLAMP}$ = 1.2 V (see *Figure 4*).

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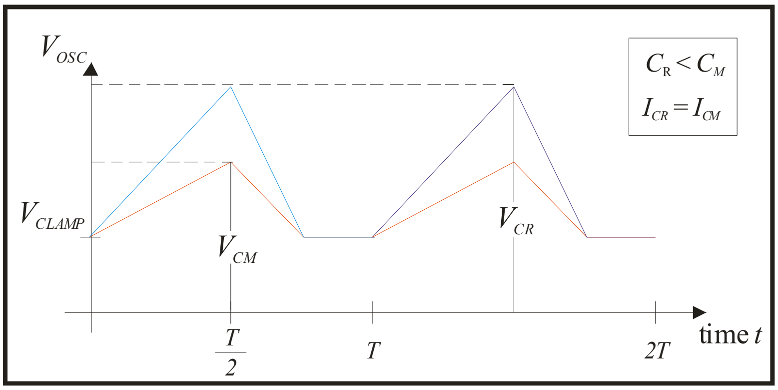


***Figure 4:*** **Integrator oscillator voltage**

The capacitive integrator currents $I_{CR}$ and $I_{CM}$ are set by external resistors $R_{CM}$, $R_{CR}$ and reference voltage $V_M$:

$$I_{CM} = \frac{V_M}{R_{CM}} \quad \text{and} \quad I_{CR} = \frac{V_M}{R_{CR}} \qquad (3)^*, (4)^*$$

Capacitors $C_M$ and $C_R$ are charged up to a maximum voltage of $V_{CM}$ and $V_{CR}$ respectively and can be calculated as follows:

$$V_{CM} = \frac{I_{CM}}{2 \cdot f_{OSC} \cdot C_M} + V_{CLAMP} \qquad (5)$$

$$V_{CR} = \frac{I_{CR}}{2 \cdot f_{OSC} \cdot C_R} + V_{CLAMP} \qquad (6)$$

The two voltages $V_{CM}$ and $V_{CR}$ are subtracted from one another in the circuit's signal conditioning unit. Via this subtraction, which is tantamount to a rectification of the procedure, $V_{CLAMP}$ is eliminated and a direct voltage of $V_{TPAS}$ is produced as an output signal after filtering.

Should $I_{CR}$ and $I_{CM}$ be the same for $C_{M,min}$ (i.e. should the reference capacitance be the same as the basic value of the measurement capacitance), on subtraction and filtering at the signal conditioning output a value of zero is obtained (see *Figure 5*).

* The equations apply to $R_{CX} = 0$ (see *Figures 7* and *8*). Should $R_{CX} \neq 0$ for the resistor due to better thermal coupling, alternative calculations are provided in the Excel spreadsheets *Kali1_cav424.exc* and *Kali2_cavV424.xls*.

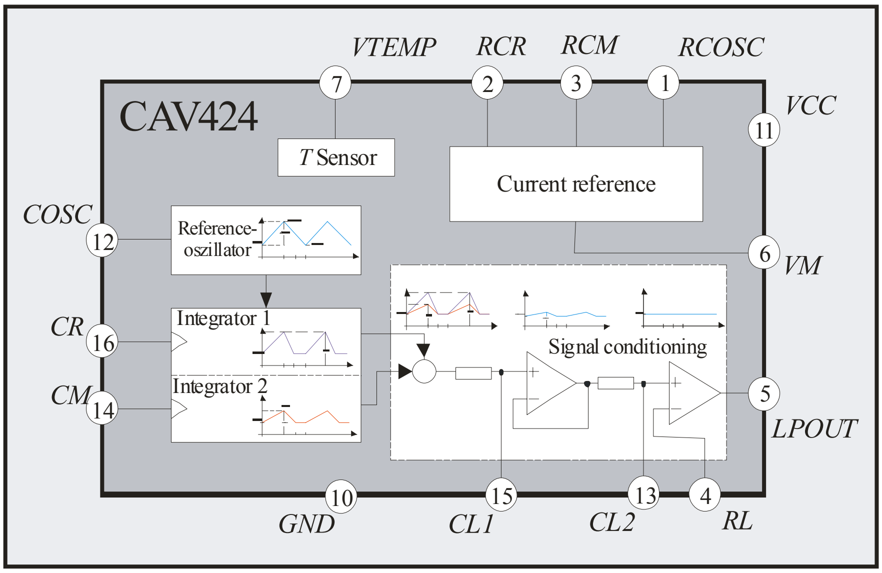


*Figure 5:* **Block diagram and signal pattern**

## Signal conditioning

The filtered and smoothed voltage has a value of $V_{TPAS}$:

$$V_{TPAS} = \frac{3}{8} \cdot (V_{CR} - V_{CM}) \tag{7}$$

Signal $V_{TPAS}$ can be boosted using the follow-on internal operational amplifier, with the amplification $G_{LP}$ being determined by resistors $R_{L1}$ and $R_{L2}$. $G_{LP}$ is calculated as:

$$G_{LP} = 1 + \frac{R_{L1}}{R_{L2}} \tag{8}$$

With (7), this results in:

$$V_{DIFF} = G_{LP} \cdot V_{TPAS} = G_{LP} \cdot \frac{3}{8} \cdot (V_{CR} - V_{CM})$$

For the output signal reference to ground (GND) it thus follows that:

$$V_{LPOUT} = V_{DIFF} + V_M \tag{9}$$

$V_{LPOUT} = f(C_M, (C_R), f_{osc}, I_{CM}, I_{CR})$, where the basic values of $C_M$ and $C_R$ must be placed in a fixed ratio. $f_{osc}$ or $I_{CM}$, $I_{CR}$ act as parameters.

**The overall transfer function (9) is accrued from equations (5) and (6). It becomes evident that the output signal is a function of capacitors $C_M$ and $C_R$, of oscillator frequency $f_{OSC}$ and of the integrator charging currents $I_{CM}$ and $I_{CR}$.**

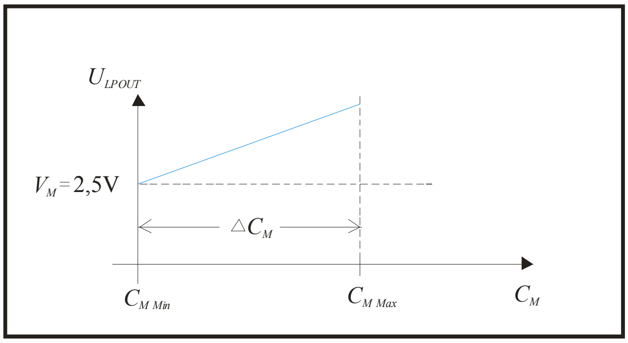


***Figure 6:*** **Output signal $V_{LPOUT}$ with $C_M > C_R$ referenced to ground**

A voltage is provided (9) as an output variable which is relative to the average voltage $V_M$. As this is ratiometric to the supply voltage, in effect a differential ratiometric output signal is obtained.

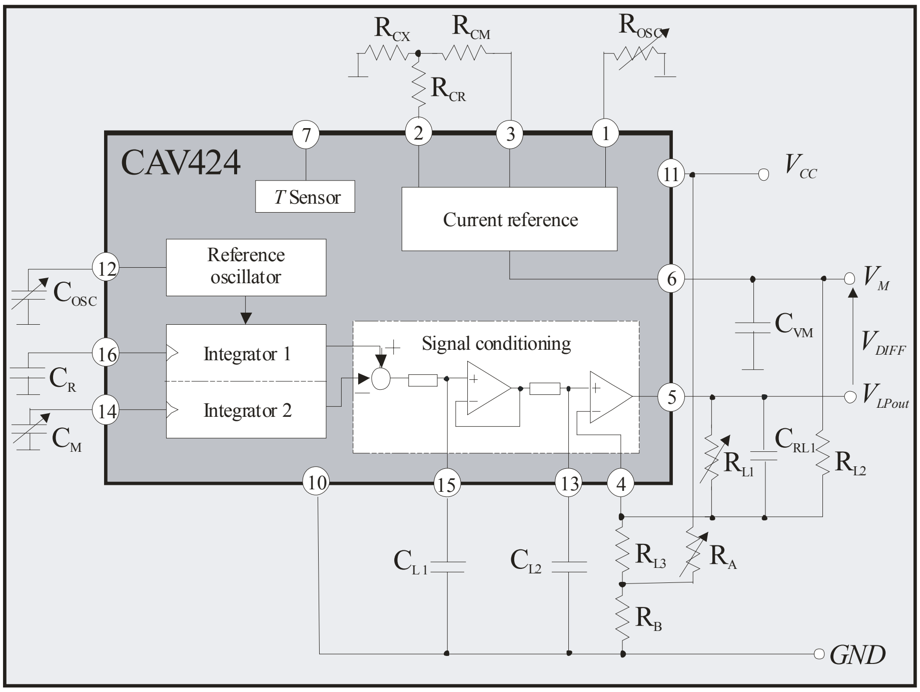


***Figure 7:*** **Functional diagram for CAV424 (with charging currents $I_{CM}$ and $I_{CR}$ constant)**

*Figure 7* assumes that the charging currents $I_{CM}$ and $I_{CR}$ are constant. This means that with a change in the basic value of the measurement capacitance $C_{M,min}$ (as is the case when different objects are measured, for example) the oscillator frequency must be adjusted to the new measurement with the alternate $C_{M,min}$ value.

If oscillator frequency $f_{osc}$ is to be set as a parameter, when $C_{M,min}$ is altered the two values $I_{CM}$ and $I_{CR}$ must also be adjusted. It is recommended that $I_{CM} = I_{CR}$. Both procedures are equally effective; the choice thereof depends on the conditions stipulated by the application.

A functional diagram is shown in *Figure 8*.

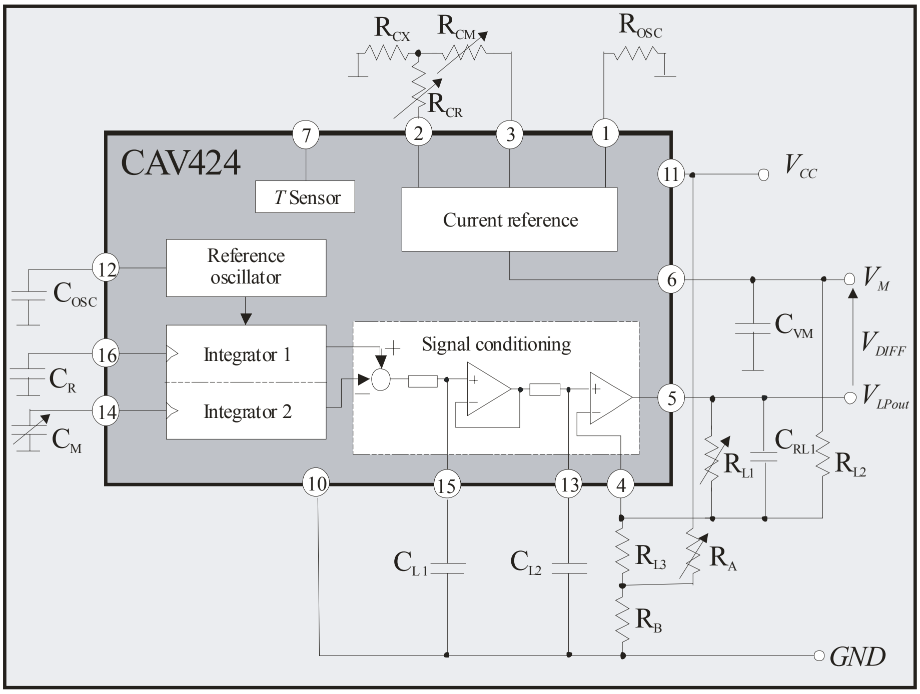


***Figure 8*: Functional diagram for CAV424 (with *fosc* constant)**

If *fosc* = constant and $I_{CM}$, $I_{CR}$ = f($C_M$, $C_R$) the same equations (1 to 9) apply as for the case that $I_{CM}$ and $I_{CR}$ = constant and *fosc* = f($C_M$, $C_R$).

For dynamic measurements with periodically changeable measurement capacitances the various frequencies must be taken into account. Among other things, the following applies:

$$f_{\text{det}} << f_{osc}$$

$f_{det}$ is the detection frequency which gives the change in measurement capacity per unit of time.



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## ELECTRICAL SPECIFICATIONS

**$T_{amb}$ = 25°C, $V_{CC}$ = 5V (unless otherwise stated)**

| Parameter | Symbol | Conditions | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|
| **Supply** | | | | | | |
| Supply Voltage | $V_{CC}$ | Ratiometric range | 4.75 | 5.00 | 5.25 | V |
| Quiescent Current | $I_{CC}$ | $T_{amb}$ = -40 ... 105°C, $G_{LP}$ = 1 | 0.6 | 1.0 | 1.4 | mA |
| **Temperature Specifications** | | | | | | |
| Operating | $T_{amb}$ | | -40 | | 105 | °C |
| Storage | $T_{st}$ | | -55 | | 125 | °C |
| **Oscillator** | | | | | | |
| Oscillator Capacitor Range | $C_{OSC}$ | $C_{OSC} = 1.6 \cdot C_M$ | 16 | | 1600 | pF |
| Oscillator Frequency Range | $f_{OSC}$ | | 1 | | 130 | kHz |
| Oscillator Current | $I_{OSC}$ | $R_{OSC}$ = 250kΩ | 9.5 | 10 | 10.75 | µA |
| **Capacitive Integrator 1 and 2** | | | | | | |
| Reference Capacitor Range | $C_R$ | | 10 | | 1000 | pF |
| Reference Capacitive Integrator Current | $I_R$ | $R_{CR}$ = 500kΩ | 4.75 | 5 | 5.38 | µA |
| Measurement Capacitor Sensitivity | $\Delta C_M$ | $\Delta C_M = (C_{M,max} - C_{M,min})/C_{M,min}$ | 5 | | 100 | % |
| Measurement Capacitor Range | $C_M$ | $C_{M,min} \leq C_M \leq C_{M,max}$ | 10 | | 2000 | pF |
| Measurement Capacitor Integrator Current | $I_M$ | $R_{CM}$ = 500kΩ | 4.75 | 5 | 5.38 | µA |
| Detection Frequency | $f_{DET}$ | $C_{L1} = C_{L2}$ =1nF | | | 2 | kHz |
| **Low Pass Stage** | | | | | | |
| Adjustable Gain | $G_{LP}$ | | 1 | | 10 | |
| Output Voltage | $V_{LPOUT}$ | $V_{LPout} = V_{Diff} + V_M$ , | 1.1 | | $V_{CC}$ – 1.1 | V |
| Corner Frequency 1 | $f_{C1}$ | $R_{01}$ = 20kΩ, $C_{L1}$ =1nF | | | 8 | kHz |
| Corner Frequency 2 | $f_{C2}$ | $R_{02}$ = 20kΩ, $C_{L2}$ =1nF | | | 8 | kHz |
| Resistive Load at PIN *LPOUT* | $R_{LOAD}$ | | 200 | | | kΩ |
| Capacitive Load at PIN *LPOUT* | $C_{LOAD}$ | | | | 50 | pF |
| Output voltage shift | $V_{DIFF}$ | VM = 2.5V | -1.4 | | 1.4 | V |
| Temperature Coefficient $V_{DIFF}$ (together with Input Stages) | $dV_{DIFF}/dT$ | $T_{amb}$ = -40 ... 105°C | | ±100 | | ppm/°C |
| Internal Resistor 1 and 2 | $R_{01}$, $R_{02}$ | | | 20 | | kΩ |
| Temperature Coefficient $R_{01,02}$ | $dR_{01,02}/dT$ | $T_{amb}$ = -40 ... 105°C | | 1.9 | | $10^{-3}$/°C |
| Ratiometric Error of $V_{LPOUT}$ | $RAT@V_{DIFF}$* | | | 0.11 | | %FS |
| **Voltage Reference $V_M$** | | | | | | |
| Voltage | $V_M$ | Ratiometric to $V_{CC}$ | | 2.5 | | V |
| $V_M$ vs. Temperature | $dV_M/dT$ | $T_{amb}$ = -40...+105°C | | ±20 | ±50 | ppm/°C |
| Current | $I_{VM}$ | Source | | | 16 | µA |
| | $I_{VM}$ | Sink | | | -16 | µA |
| Load Capacitance | $C_{VM}$ | | 80 | 100 | 120 | nF |
| Ratiometric Error of $V_M$ | $RAT@V_M$** | | | 0.007 | | %FS |

* ***RAT @ $V_{DIFF}$*** = 2 [1.05 $V_{DIFF}$($V_{CC}$ = 5V) – $V_{DIFF}$($V_{CC}$ = 5.25V)]/[$V_{DIFF}$($V_{CC}$ = 5V) + $V_{DIFF}$($V_{CC}$ = 5.25V)]
** *RAT @ $V_M$* = 2 [1.05 $V_M$($V_{CC}$ = 5V) – $V_M$($V_{CC}$ = 5.25V)]/[$V_M$($V_{CC}$ = 5V) + $V_M$($V_{CC}$ = 5.25V)]


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| Parameter | Symbol | Conditions | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|
| **Temperature Sensor $V_{TEMP}$** | | | | | | |
| Voltage | $V_{TEMP}$ | $R_{TEMP} \geq 50M\Omega$ | 2.20 | 2.32 | 2.45 | V |
| Sensitivity | $dV_{TEMP}/dT$ | $R_{TEMP} \geq 50M\Omega$ | | 8 | | mV/°C |
| Thermal Nonlinearity | | $R_{TEMP} \geq 50M\Omega$, end point method | | 0.5 | | %FS |

***Table 1*: Specifications for CAV424**

Note:
1) The oscillator capacity has to be chosen using $C_{OSC} = 1.6 \cdot C_{M,Min}$
2) The capacitor range of $C_M$ and $C_R$ can be extended, whereby the system performance is reduced and the electrical limits are exceeded.
3) Currents flowing into the IC are negative.
4) $R_{TEMP}$ is the minimum load resistance at pin *VTEMP*.

The system performance over temperature forces resistors $R_{CR}$, $R_{CM}$ and $R_{OSC}$ to have the same temperature coefficient; this also requires that the components are placed very close together in the circuit. Capacitors $C_R$, $C_M$ and $C_{OSC}$ are also obliged to have the same temperature coefficient and a very close proximity on the circuit board.

## STANDARD DIMENSIONING

For external elements which do not have to be altered dependent on the measurement capacity the following standard values apply:

| Parameter | Symbol | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|
| Output Stage Resistor (1%) | $R_{L2}$, $R_{L3}$ | | 100 | | kΩ |
| Offset Resistor (1%) | $R_B$ | | 100 | | kΩ |
| Reference Voltage Capacity ($V_M$ = 2.5V) | $C_{VM}$ | 80 | 100 | 120 | nF |
| Filter Capacitance | $C_{RL1}$ | | 2.2 | | nF |

***Table 2:* Standard values for external components**

## BOUNDARY CONDITIONS

| **Parameter** | Symbol | Condition | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|
| Maximum Supply Voltage | $V_{CCmax}$ | | | | 17 | V |
| Oscillator Frequency Range | $f_{OSC}$ | | 1 | | 130 | kHz |
| Reference Capacitive Integrator Current | $I_R$ | $R_{CR}$ = 500kΩ | | | 5.38 | µA |
| Measurement Capacitor Integrator Current | $I_M$ | $R_{CM}$ = 500kΩ | | | 5.38 | µA |

***Table 3:* Boundary conditions**


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## DIMENSIONING PROCEDURE

**Programs *Kali1_cav424.xls* and *Kali2_cav424.xls* can be used for dimensioning purposes.**

The dimensioning process takes the following scenarios into account:

a) **Kali1_cav424.xls** – The integrator charging currents $I_{CM}$ and $I_{CR}$ are given and constant. Oscillator frequency *fosc* must be adjusted to suit the minimum value of measurement capacitance $C_{M,min}$.

b) **Kali2_cav424.xls** – Oscillator frequency *fosc* is given and determined and integrator charging currents $I_{CM}$ and $I_{CR}$ must be adjusted to suit the minimum value of measurement capacitance $C_{M,min}$.

In a) the dimensioning process assumes that in addition to measurement capacitors $C_M$ and $C_R$ parasitic capacitances in both the IC and measurement circuit also influence the signal pattern. When dimensioning on the basis of the given equations a deviation from the theoretical value in the output characteristic must thus be reckoned with.

For this reason a calibration algorithm has been developed (*Kali1_cav424.xls*) which at constant integrator charging currents ($I_{CM}$ and $I_{CR}$) calculates a suitable oscillator frequency of *fosz* depending on the minimum value of $C_{M,min}$ (basic capacitance). It then dimensions the resistors for the offset and signal span in such a way that the output signal adopts the required values.

Compensation of the sensor system is carried out in two stages. In *stage one* a calibration operating point is defined, during which process oscillator frequency *fosc* is calculated depending on minimum measurement capacitance $C_{M,min}$. To this end the minimum and maximum values ($C_{M,min}$ and $C_{M,max}$) are entered in the Excel spreadsheet. The oscillator frequency, oscillator capacitance $C_{OSC}$ and oscillator resistance $R_{OSC}$ are then output.

In addition low pass filter capacitances $C_{L1}$ and $C_{L2}$ are calculated which are dependent on the oscillator frequency. It is sufficient if these values are computed once for the largest expected value of minimum basic capacitance $C_{M,min}$ (for example during one production batch) and the relevant capacitors added to the circuit. The maximum signal frequency is also determined by which the measurement capacitance is permitted to change.

Taking the given and calculated external components and particularly predefined precision resistors $R_{L1(mess)}$ and $R_{L2(mess)}$ we can calculate the output voltage $V_{LPOUT(mess)}$.

***NB*: $R_{L1(mess)}$** and $R_{A(mess)}$ must both be 100kOhm precision resistors with a tolerance of 0.1% maximum.

Output signal values $V_{LPOUT(mess)}$ are now entered in *stage two* of the calibration program. Using the measured values the algorithm now calculates the setpoint for the two calibration resistors $R_{L1}$ and $R_A$ which replace precision resistors $R_{L1(mess)}$ and $R_{L2(mess)}$ and must be individually mounted. Depending on the accuracy requirements of the setup their values should match those calculated as closely as possible.

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Once the two calibration resistors $R_{L1}$ and $R_A$ have been replaced by precision resistors $R_{L1(mess)}$ and $R_{L2(mess)}$ the system is calibrated to the required output value – with all parasitic effects and tolerances taken into account.

In *stage one* of b), at a given fixed oscillator frequency calibration spreadsheet *Kali2_cav424.xls* calculates the values of integration currents $I_{CM}$ and $I_{CR}$ which can be achieved by setting resistors $R_{CM}$ and $R_{CR}$. Using these values and the other external elements output voltage $V_{LPOUT(mess)}$ is measured and the value entered into the calibration program. The rest of stage two is identical to the calibration procedure described in a).

## INITIAL OPERATION

Initial operation is described in detail in the description of the calibration program (see *Kali1_cav424.xls* and *Kali2_cav424.xls*).

## OUTPUT VOLTAGES

The following applies for the output voltage (9):

$$V_{LPOUT} = V_{DIFF} + V_M$$

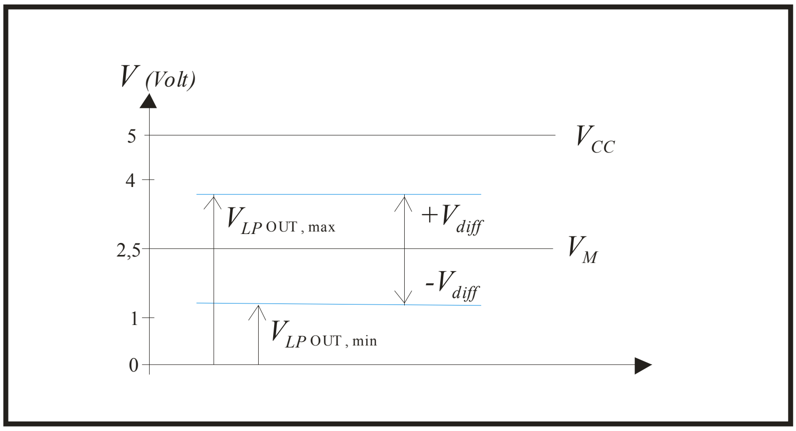


***Figure 9:*** **Output voltages**

If $V_M$ = 2.5V, according to the specifications the schematic shown in *Figure 9* is generated.

## EXAMPLE APPLICATIONS

### Application: EMC protection for CAV424

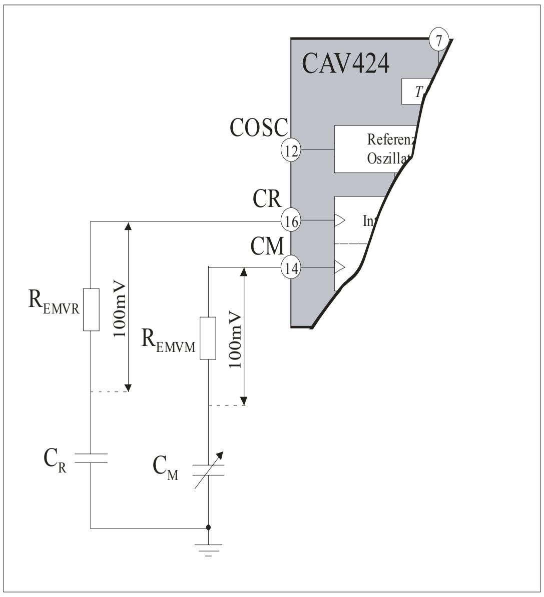


***Figure 10:*** **Protective EMC circuitry for CAV 424**

When measuring capacitance the electrodes are receptive to high-frequency disturbances such as aerials. Measures must thus be taken to protect these high impedance inputs.

To protect against EMC resistors $R_{EMVM}$ and $R_{EMVR}$ are plugged into the supply lines servicing external capacitors $C_M$ and $C_R$. Together with the parasitic and internal capacitances these act as low passes and thus suppress high-frequency disturbance factors.

The following applies:

$$R_{EMVM} = \frac{0.1V}{I_{CM}} \quad \text{and} \quad R_{EMVR} = \frac{0.1V}{I_{CR}}$$

Further protective EMC measures are not required for industrial applications.

As CAV424 has been manufactured using bipolar technology the IC is robust with regard to ESD.

# CAV424 - C/U transducer IC
# with adjustable output voltage

## BLOCK DIAGRAM AND PINOUT

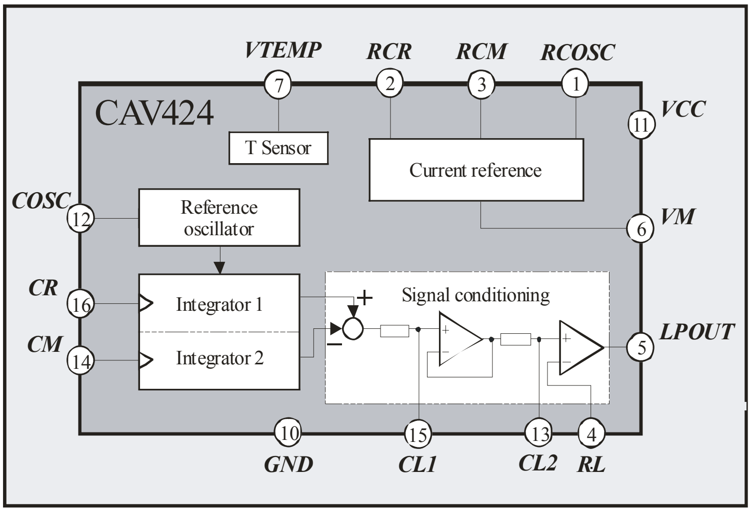


***Figure 11:*** **Block diagram of CAV424**

| PIN | NAME | DESCRIPTION |
|---|---|---|
| 1 | *RCOSC* | Oscillator current definition |
| 2 | *RCR* | Current setting for integrator $C_R$ |
| 3 | *RCM* | Current setting for integrator $C_M$ |
| 4 | *RL* | Gain setting |
| 5 | *LPOUT* | Output |
| 6 | *VM* | Reference voltage 2.5V |
| 7 | *VTEMP* | Temperature sensor |
| 8 | *N.C.* | Not connected |
| 9 | *N.C.* | Not connected |
| 10 | *GND* | IC ground |
| 11 | *VCC* | Supply voltage |
| 12 | *COSC* | Oscillator capacitance |
| 13 | *CL2* | Low pass 2, corner frequency |
| 14 | *CM* | Measurement capacitance |
| 15 | *CL1* | Low pass 1, corner frequency |
| 16 | *CR* | Reference capacitance |

***Table 4*****: CAV424 pinout**

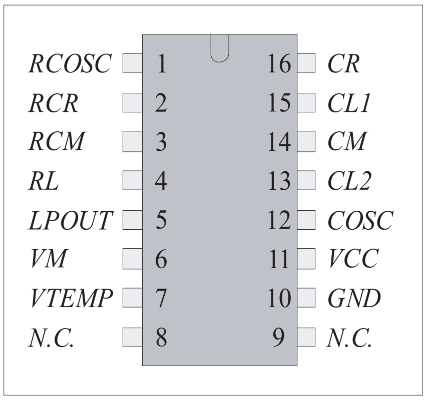


***Figure 12:*** **CAV424 pinout**


analog microelectronics
integrated circuits

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# CAV424 - C/U transducer IC
# with adjustable output voltage

## DELIVERY

CAV424 is available as:

- SO16 (n)
- Dice on 5" blue foil
- For sample batches CAV424 can be supplied on a DIL16 SO16 adapter (CAV424Adapt)

Package dimensions: see http://www.analogmicro.de/products/analogmicro.de.en.package.pdf

## ADDITIONAL EQUIPMENT

For design purposes, by way of support Analog Microelectronics GmbH can also supply a breadboard (**BBCAV424**) which has been assembled for a set of parameters but which can also be used for individual measurements.

## FURTHER READING

Please see our website for further information (www.analogmicro.de):


[1] AN1008 application notes

[2] PR1009 press release





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