Confidential

ADI MEMS 产品原理及应用介绍

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议程

1. 什么是MEMS?

2. MEMS加速度计工作原理

3. MEMS加速度计应用

4. MEMS陀螺仪工作原理

5. ADI高性能IMU以及应用

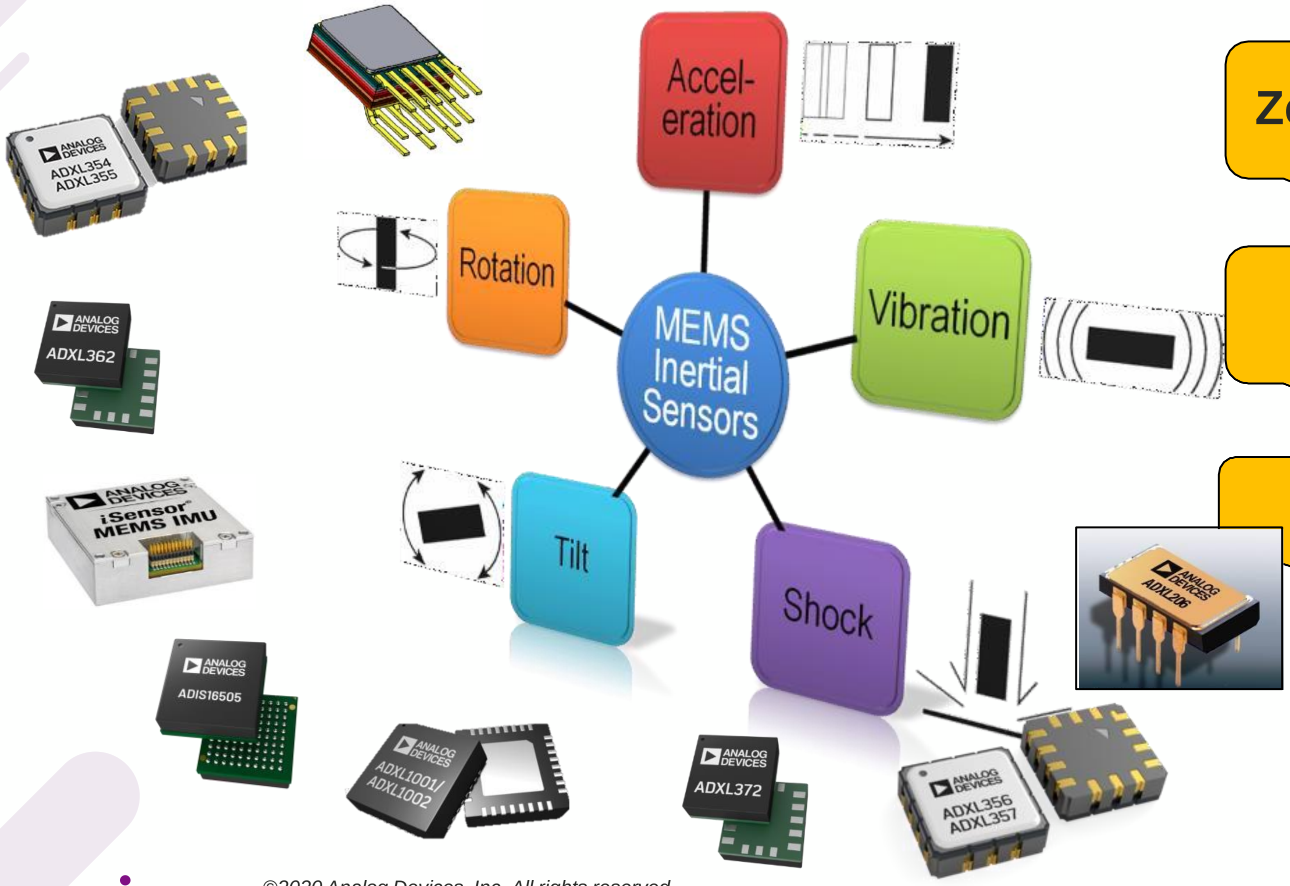
什么是 MEMS？

MEMS全称Micro Electromechanical System，微机电系统。是指尺寸在几毫米乃至更小的高科技装置，其内部结构一般在微米甚至纳米量级，是一个独立的智能系统。

MEMS主要由传感器、作动器（执行器）和微能源三大部分组成。微机电系统涉及物理学、半导体、光学、电子工程、化学、材料工程、机械工程、医学、信息工程及生物工程等多种学科和工程技术，为智能系统、消费电子、可穿戴设备、智能家居、系统生物技术的合成生物学与微流控技术等领域开拓了广阔的用途。

常见的产品包括MEMS加速度计、MEMS压力传感器、MEMS陀螺仪、MEMS湿度传感器等以及它们的集成产品.微机电系统在国民经济方面将有着广泛的应用前景。主要民用领域是电子、医学、工业、汽车和航空航天系统。MEMS具有以下几个基本特点，微型化、智能化、多功能、高集成度和适于大批量生产。

MEMS传感器的功用



Zero Power

Zero Space

Cost Nothing

Last for Ever

Secure

Trusted

MEMS 加速度计

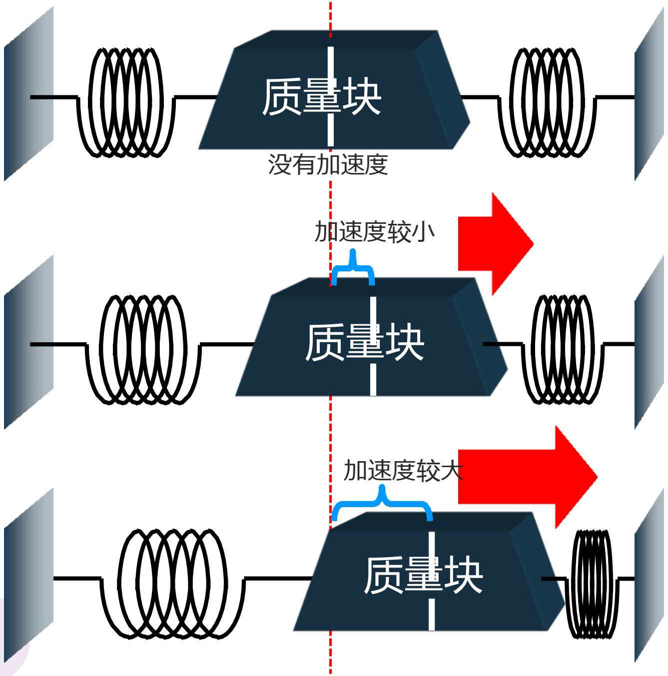
MEMS 加速度计是怎么工作的?

MEMS 加速度计

- 加速度计测量物体相对运动
  - 比如，当火车加速离开车站的时候，乘客会与火车发生相对运动。

MEMS 加速度计

- 加速度计测量物体相对运动
  - 相对运动的距离会与产生加速度的力成正比



MEMS 加速度计

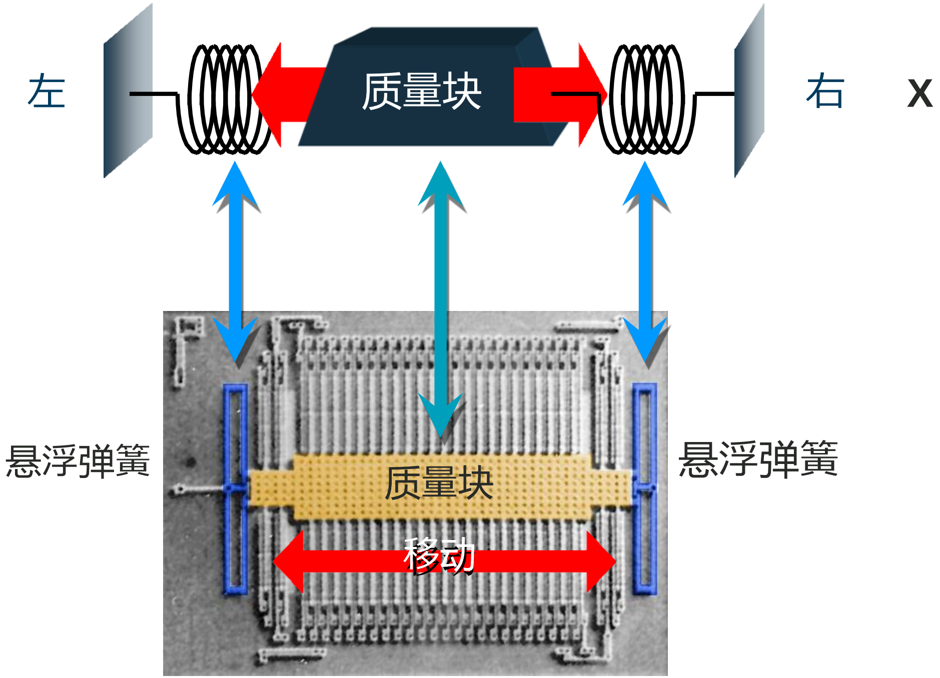
- 胡克定律
  - 定律内容：在弹性限度内，物体的形变跟引起形变的外力成正比。
  - 公式：F=-kx，其中k是物质的弹性系数，它由材料的性质所决定，负号表示弹簧所产生的弹力与其伸长（或压缩）的方向相反。

- 牛顿第二定律
  - 定律内容：物体的加速度a跟物体所受的合外力F成正比，跟物体的质量m成反比，加速度的方向跟合外力的方向相同。
  - 公式：F=ma

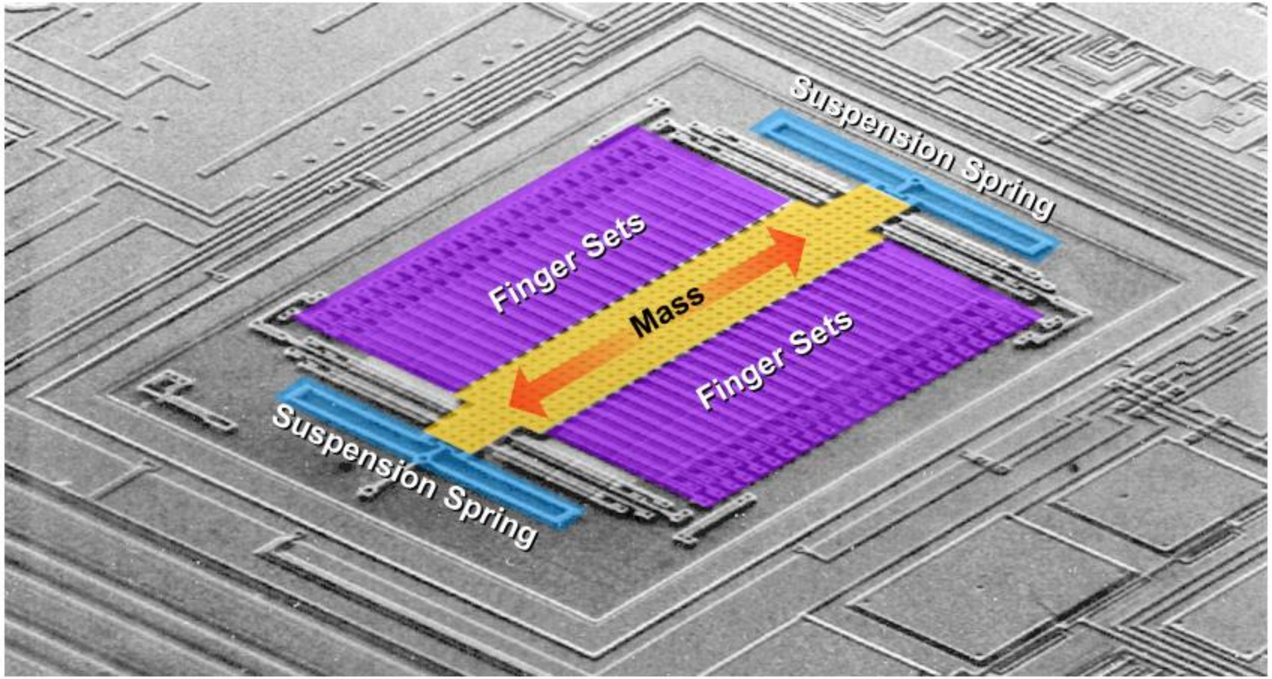
加速度 = 形变量×劲度系数÷质量

MEMS 加速度计

- 单轴加速度计内采用相同的组件
  - 左 / 右 (X轴)

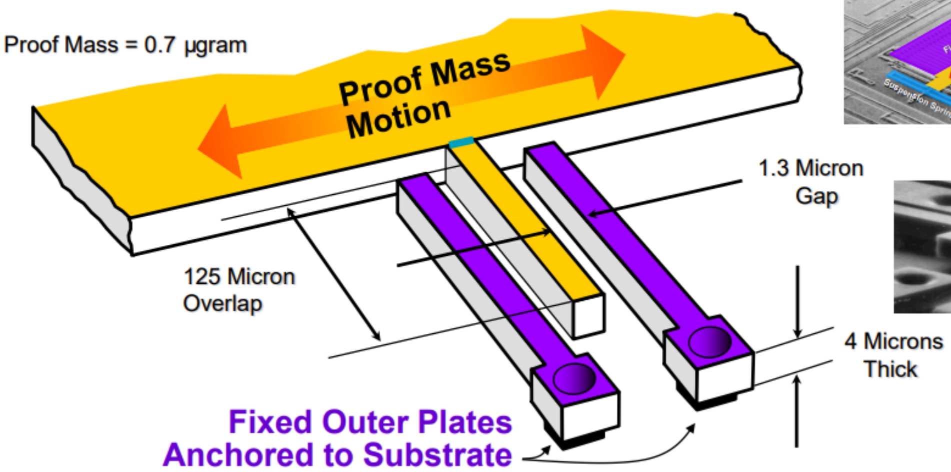


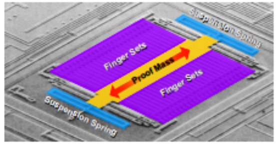
MEMS 加速度计


Suspension Spring
Finger Sets
Mass
Finger Sets
Suspension Spring

MEMS 加速度计

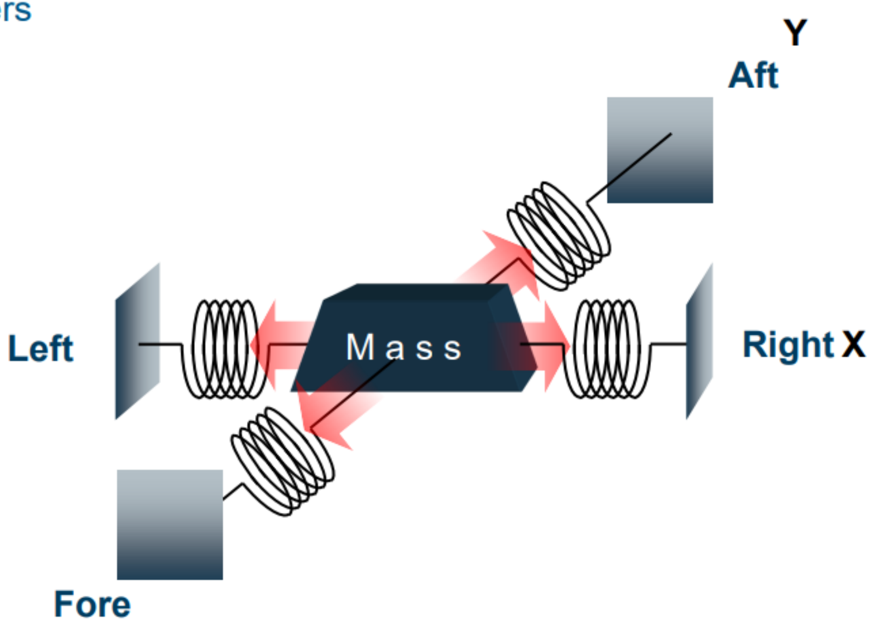
- Single finger set
- There are 30 pairs of differential capacitor at every axis
- The total capacitance is 64fF





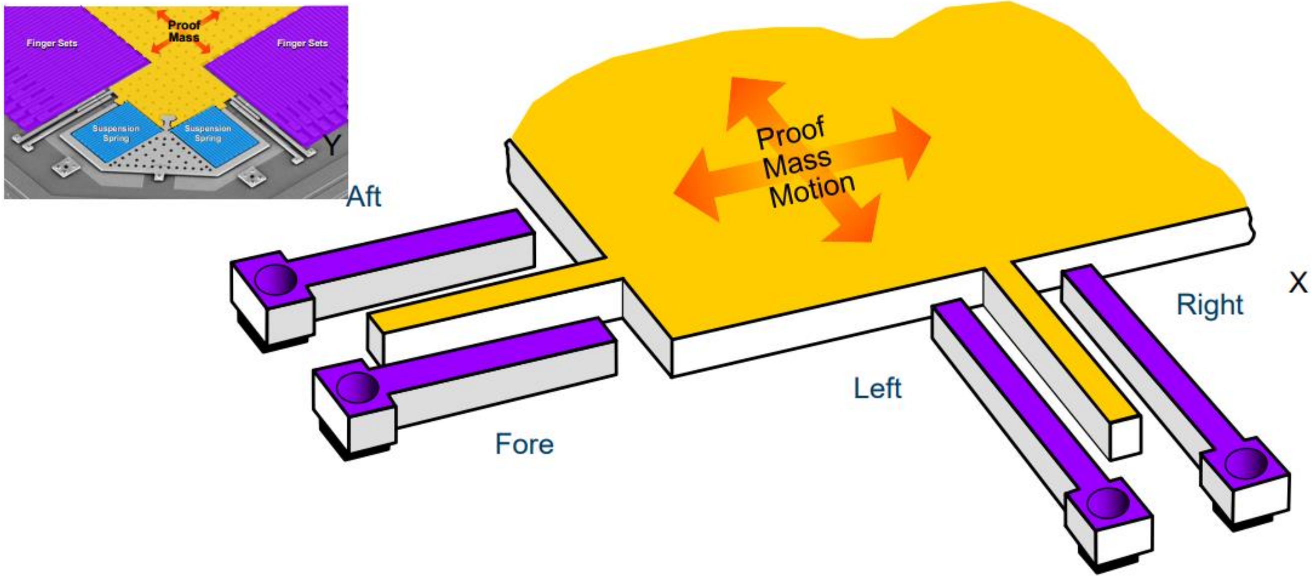
MEMS 加速度计

2-Axis Accelerometers



MEMS 加速度计

2-Axis Accelerometers



Here is (highly exaggerated) compound motion along the X and Y axes.

MEMS 加速度计

- 如何用一个机械传感器测量多轴加速度
  - 弹簧，质量块，fingers被安排成可在X、Y、Z三个方向运动
  - 在X、Y轴上（与芯片的平面平行），通过测量运动finger和固定finger 间的电容变化来获得位移信息，进而得到加速度。
  - 在Z轴上，通过测量运动质量块和基片间的电容变化来获得位移信息， 进而得到加速度。

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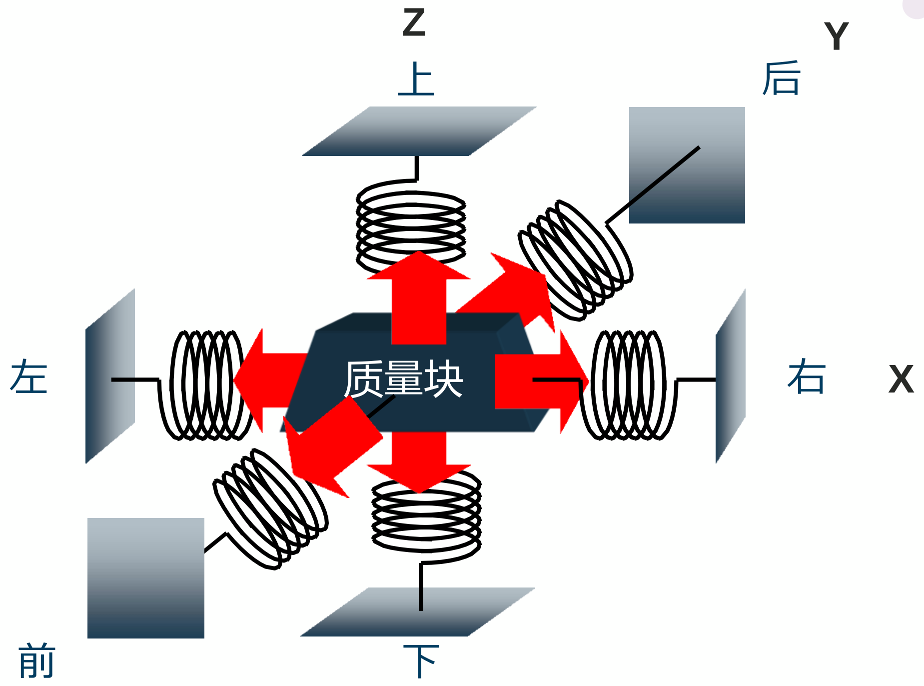
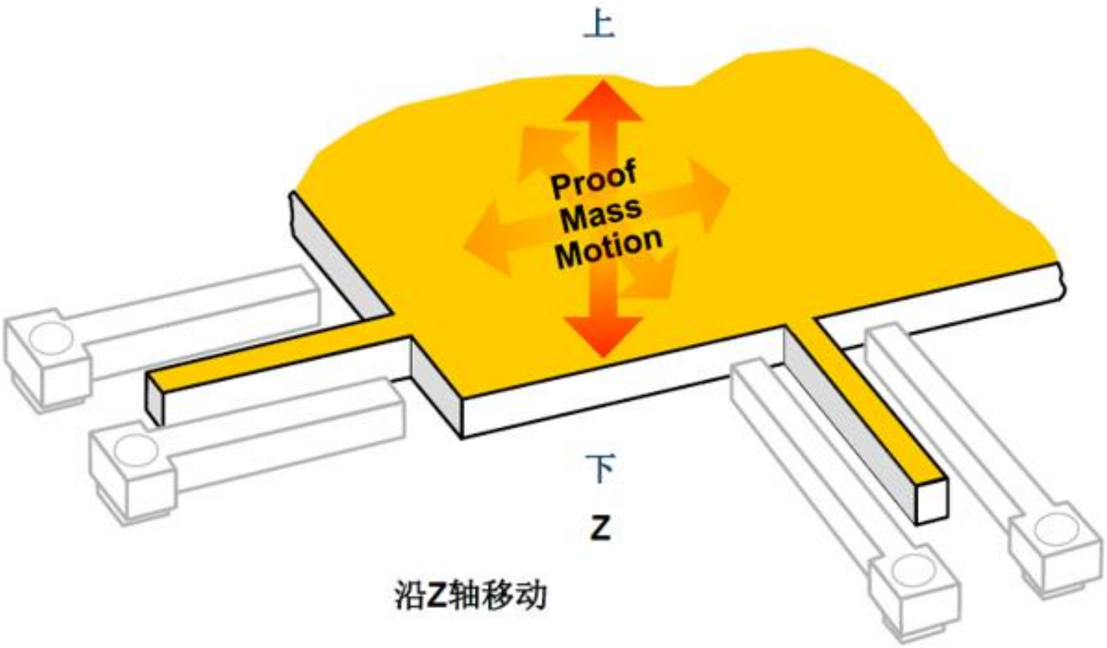
MEMS 加速度计

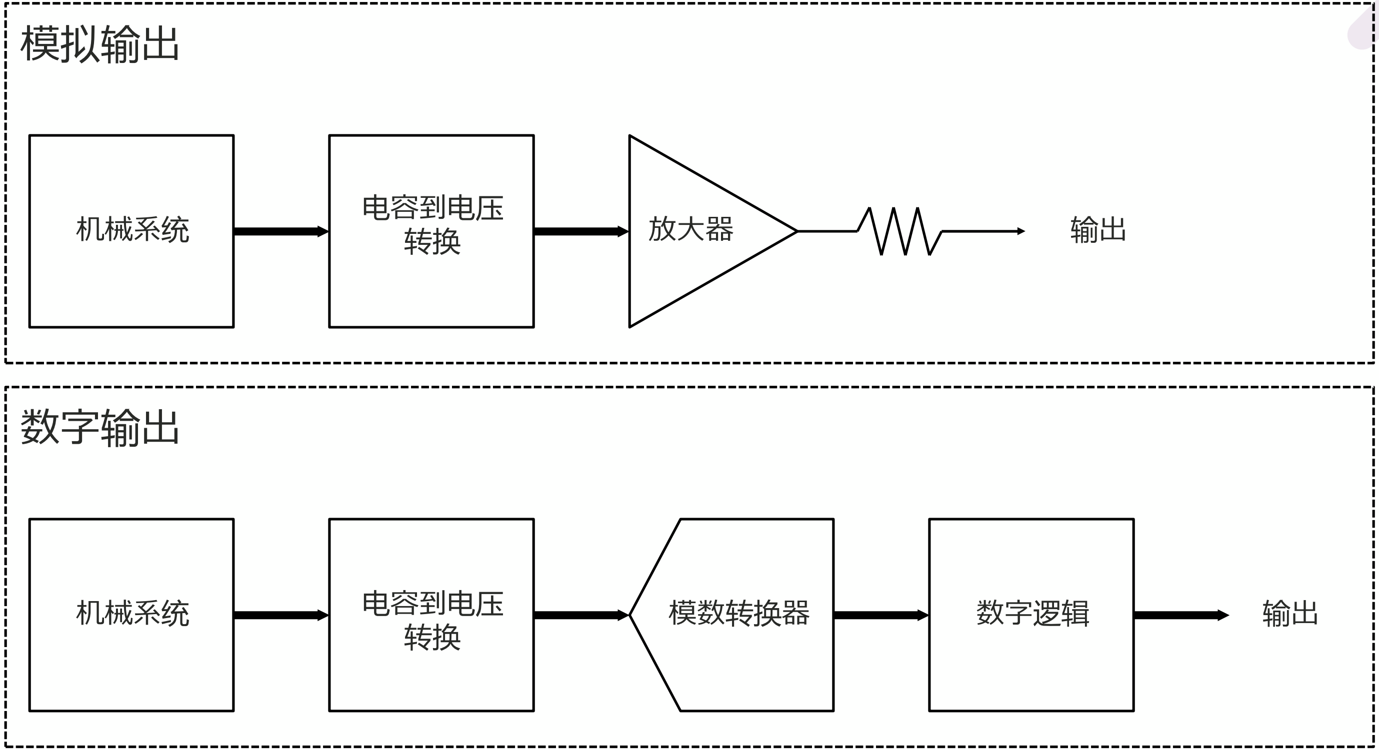
- ► 三轴加速度计
  - ▪ 左 / 右 (X)
  - ▪ 前 / 后 (Y)
  - ▪ 上 / 下 (Z)



MEMS 加速度计



MEMS 加速度计



MEMS 加速度计参数　ADXL355为例

Parameter	Test Conditions/Comments	Min	Typ	Max	Unit
SENSOR INPUT	Each axis				
Output Full Scale Range (FSR)	User selectable		±2.048		*g*
			±4.096		*g*
			±8.192		*g*
Nonlinearity	±2 *g*		0.1		% FS
Cross Axis Sensitivity			1		%
SENSITIVITY	Each axis				
X-Axis, Y-Axis, and Z-Axis Sensitivity	±2 *g*	235,520	256,000	276,480	LSB/*g*
	±4 *g*	117,760	128,000	138,240	LSB/*g*
	±8 *g*	58,880	64,000	69,120	LSB/*g*
X-Axis, Y-Axis, and Z-Axis Scale Factor	±2 *g*		3.9		µg/LSB
	±4 *g*		7.8		µg/LSB
	±8 *g*		15.6		µg/LSB
Sensitivity Change due to Temperature	−40°C to +125°C		±0.01		%/°C
0 *g* OFFSET	Each axis, ±2 *g*				
X-Axis, Y-Axis, and Z-Axis 0 *g* Output		−75	±25	+75	mg
0 *g* Offset vs. Temperature (X-Axis, Y-Axis, and Z-Axis)[1]	−40°C to +125°C	−0.15	±0.02	+0.15	mg/°C
Repeatability[2]	X-axis and y-axis		±3.5		mg
	Z-axis		±9		mg
Vibration Rectification[3]	±2 *g* range, in a 1 *g* orientation, offset due to 2.5 *g* rms vibration		<0.4		*g*
NOISE DENSITY	±2 *g*				
X-Axis, Y-Axis, and Z-Axis			25		µg/√Hz

VRE 振动整流误差

- ► 振动整流误差就是加速度计在振动条件下所引起的零点偏移
- ► 振动整流误差 = 有振动下平均输出 – 无振动下的平均输出
  - ▪ **小的振动整流误差可以简化系统的减震设计**

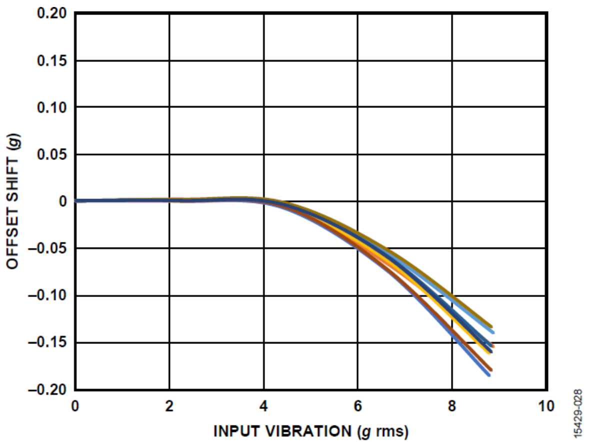


Figure 28. ADXL356 Vibration Rectification Error (VRE), Z-Axis Offset from +1 g, ±10 g Range, Z-Axis Orientation = +1 g

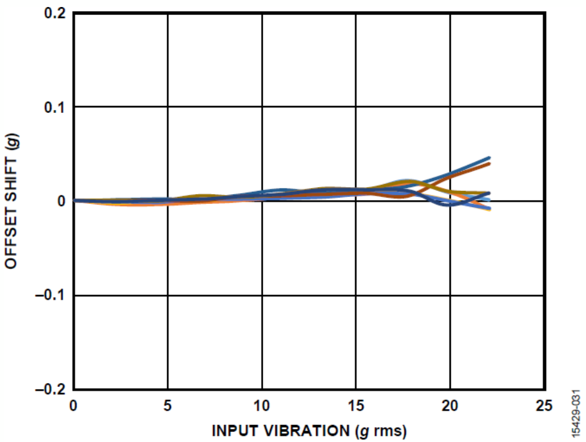
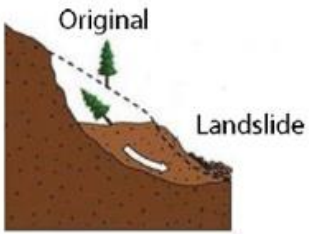


Figure 31. ADXL356 Vibration Rectification Error (VRE), Z-Axis Offset from +1 g, ±40 g Range, Z-Axis Orientation = +1 g

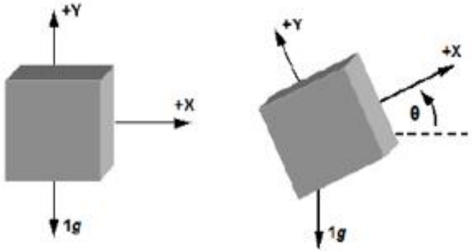
MEMS 加速度计应用

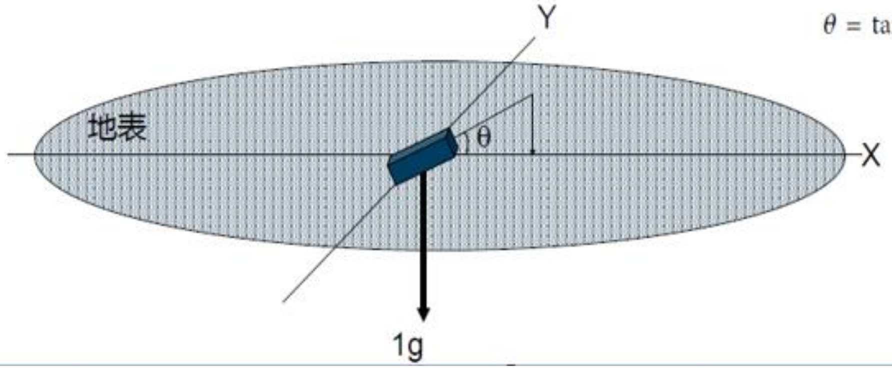
- 倾角检测

倾角检测应用场景



倾角检测原理





$$\theta = \sin^{-1}\left(\frac{A_{X,OUT}[g]}{1g}\right)$$

$$\theta = \tan^{-1}\left(\frac{A_{X,OUT}}{A_{Y,OUT}}\right)$$

$$\theta = \tan^{-1}\left(\frac{A_{X,OUT}}{\sqrt{A^2_{Y,OUT} + A^2_{Z,OUT}}}\right)$$

倾角检测误差源

- 常见问题：加速度计的精度是多少？
  - 内核传感器和算法影响系统精度
    - 一些误差是可见的，可以通过后处理来降低：
      - 初始的零点偏移
      - 由于焊接造成的零点偏移
      - PCB装配和系统装配造成的零点偏移
      - 零点温漂
      - 灵敏度误差
      - 灵敏度温漂
      - 非线性
      - 交调灵敏度

      …

    - 难以校正的误差源：
      - 噪声
      - 温度回滞特性
      - 零点在产品生命周期内的漂移
      - 灵敏度在产品生命周期内的漂移
      - 零点受湿度的影响
      - PCB形变

      …

加速计校准原理

校准零偏度和灵敏度

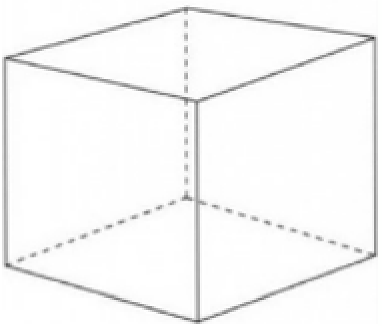
- 提供X = 1Gee, X= -1Gee, Y = 1Gee, Y = -1Gee, Z = 1Gee, Z = -1Gee六个基准面。

$$A_{OUT}[g] = A_{OFF} + (Gain \times A_{ACTUAL})$$

$$A_{+1g}[g] = A_{OFF} + (1\,g \times Gain)$$
$$A_{-1g}[g] = A_{OFF} - (1\,g \times Gain)$$

$$A_{OFF}[g] = 0.5 \times (A_{+1g} + A_{-1g})$$
$$Gain = 0.5 \times \left(\frac{A_{+1g} - A_{-1g}}{1g}\right)$$

$$A_{ACTUAL}[g] = \frac{A_{OUT} - A_{OFF}}{Gain}$$



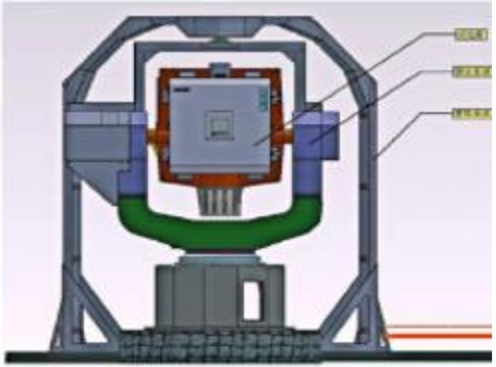
加速计校准原理

校准零偏度，灵敏度和交调灵敏度

$$A_{+1g}[g] = A_{OFF} + (1\,g \times Gain)$$
$$A_{-1g}[g] = A_{OFF} - (1\,g \times Gain)$$

$$A_{OFF}[g] = 0.5 \times (A_{+1g} + A_{-1g})$$
$$Gain = 0.5 \times \left(\frac{A_{+1g} - A_{-1g}}{1\,g}\right)$$

$$A_{ACTUAL}[g] = \frac{A_{OUT} - A_{OFF}}{Gain}$$

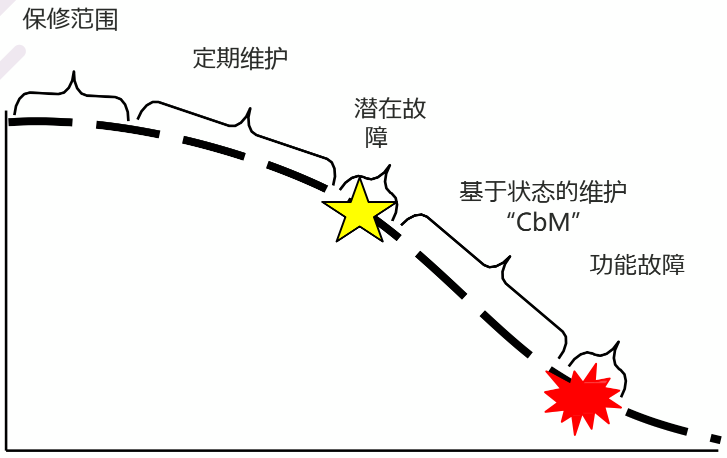


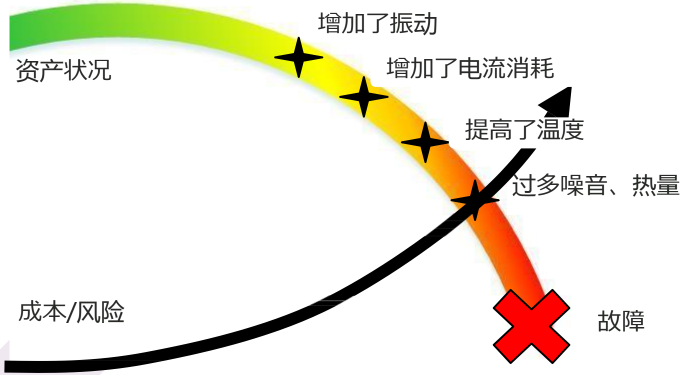
$$\begin{bmatrix} ActualX \\ ActualY \\ ActualZ \end{bmatrix} = \begin{bmatrix} XX & XY & XZ \\ YX & YY & YZ \\ ZX & ZY & ZZ \end{bmatrix} * \begin{bmatrix} 1/S_x & 0 & 0 \\ 0 & 1/S_y & 0 \\ 0 & 0 & 1/S_z \end{bmatrix} * \begin{bmatrix} OUTX - OFFX \\ OUTY - OFFY \\ OUTZ - OFFZ \end{bmatrix}$$

MEMS 加速度计应用

- 预测性维护

常见术语 CbM, CM, PdM, PM





CbM**不是**...	CbM是...
不是仅传感器解决方案	系统解决方案
不仅限于振动	完整的诊断解决方案

传统维护和预测性维护

过去...

事后维护

预防性

现在

扩展机会

最关键设备

中/高端设备： 轴承、电机、泵...

更小、更廉价的设备

持续监测

预测性

传统维护和预测性维护成本对比

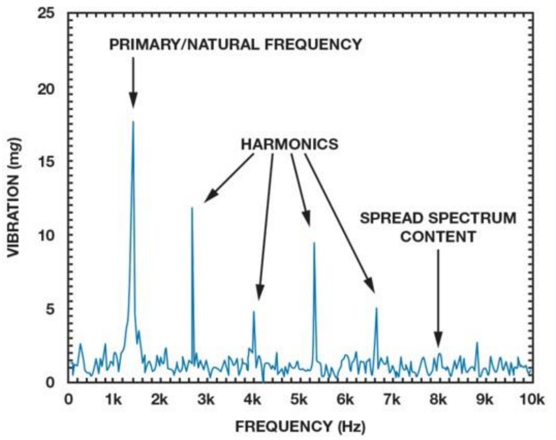
表2. 纠正性、预防性和预测性维护的成本对比

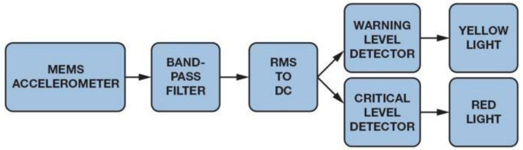
	启动/安装成本	操作成本	与计划外停机相关的成本
纠正性维护			$$$$$$$$$$ 计划外生产停机
预防性维护		$$ 根据计划进行现场干预/ 系统性地更换易损件	$$$$ 未能进行实时机器监控 导致出现预期外的生产停机
预测性维护	$$ 特定设备的安装 (振动传感器等)	$ 机器状态信息，通过特定软件或 通过AI进行监控	$ 实时机器监测； 妥善计划的生产停机

振动监测关注的指标

噪声、带宽、量程是关键

- 振动测量一般意味着对频谱进行勘测，以确定轴承、齿轮或润滑是否出现故障。
- 最终应用是**机器健康/状态监测**。
- 传感器关键性能要求有：
  - ➢ 超低噪声
  - ➢ 更高频率运行（了解超出其他伪像的轴承噪声）
  - ➢ 更高动态范围（给定位移时，加速度与频率平方成正比）





高频振动产生很大加速度 - 加速度 = -4兀^2 * f^2 * 位移

——例如，100 Hz振动和1μm位移

-- A = 4 * 兀^2 * $(10^2)^2$ * 10^{-7} = 0.395g

——1 kHz振动将产生100倍的加速度！

-- A = 4 * 兀^2 * $(10^3)^2$ * 10^{-7} = 39.5g

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轴承失效特点

检测轴承中的早期故障需要宽带宽、低噪声传感器

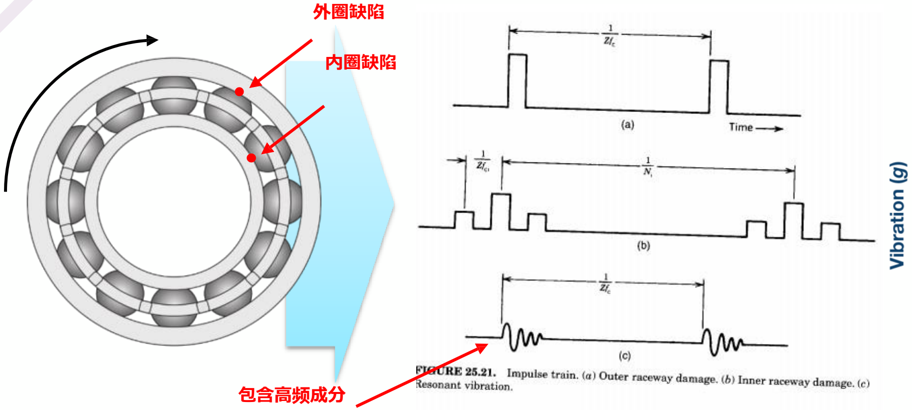
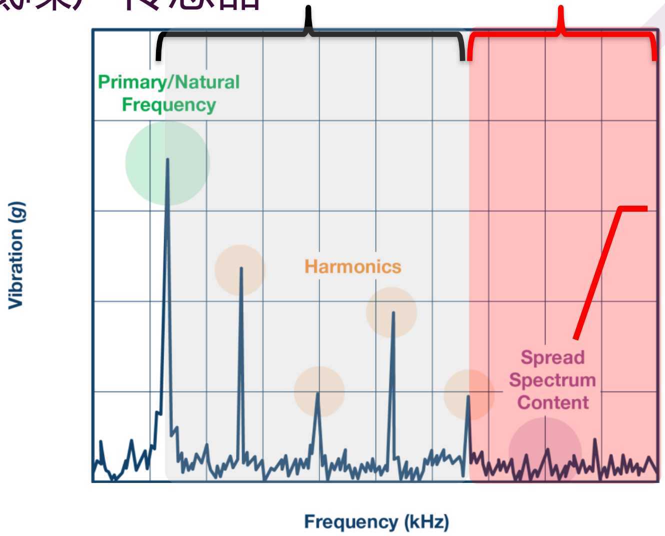


FIGURE 25.21. Impulse train. (a) Outer raceway damage. (b) Inner raceway damage. (c) Resonant vibration.



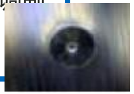
测量是在最高10 kHz甚至更高的频率进行，因为人们关注的振动分量位于较高频率

第1阶段

- 存在高频
  - 通常远大于5kHz
- 幅度非常低

第2阶段

- 由冲击产生的振铃效应增加
  - 500Hz至5kHz
- 缺陷频率出现并有调制效应



第3阶段

- 能量传播到较低频率
- 缺陷频率的幅度增加
- 轴承温度升高

第4阶段

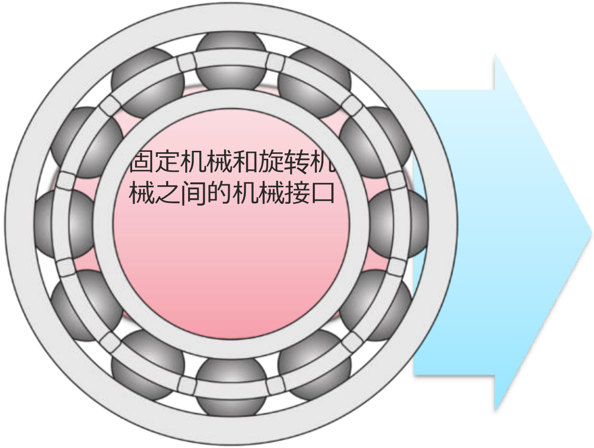
- 第一频带中的缺陷频率显著提高
- 本底噪声增加

失效迫在眉睫！

轴承在机械设备中的作用

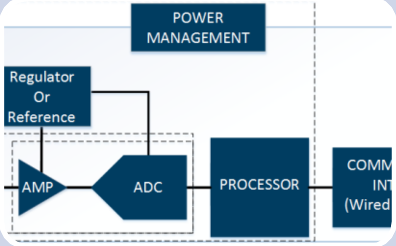
工业和商业应用中>90%的旋转机械
使用滚动元件轴承*

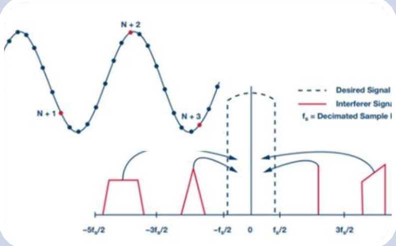
* Graney，Starry， “滚动元件轴承分析”

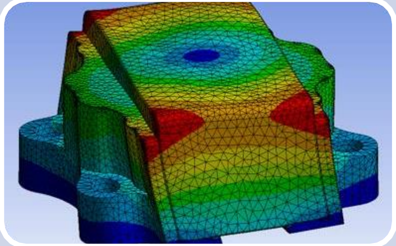


对
- 支持负载
- 保持间隙至关重要

CbM应用ADI能提供的解决方案







传感器

- 新一代高性能加速度计
  - 宽带宽，低噪声，大量程
  - ADXL1001/2/3/4/5
  - ADXL356/7

信号链

- 完整信号链提供系统级方案
  - 运放
  - ADCs
  - 电源
  - 处理器
  - 通信
    - 有线和无线

信号处理

- 考虑传感器性能最优化
- 实时处理提供数据洞察
  - 时域和频域
- 可扩展能力增强用户接口

封装

- 机械设计考虑支持工业环境
- 全带宽的性能优化
- 最佳系统性能考量

ADcmXL3021
ADcmXL1021-1

选择合适的加速度计

表1. ADcmXL3021和ADXL100x系列非常适合CbM应用。

系列	主要特性	应用/维护类型	轴数	输出类型
ADXL1001/ADXL1002/ADXL1003/ADXL1004/ADXL1005	高带宽、低噪声、100 *g*至500 *g*、带宽高达24 kHz (具体取决于产品)	非常适合用于在旋转机器上实施预测性维护；可以检测出早期故障症状	单轴	模拟
ADXL354/ADXL355/ADXL356/ADXL357	低噪声、低失真、低功耗；最高±40 *g*；1500 Hz带宽	诊断系统故障，例如低速旋转设备的不平衡、失调、松动和中后期轴承故障	三轴	模拟或数字 (具体取决于产品)
ADXL335/ADXL337	低功耗、小尺寸、模拟接口、3 *g*	面向需要模拟接口的低成本应用	三轴	模拟
ADXL343/ADXL344/ADXL345/ADXL346	入门级、低成本、±2 *g*、±4 *g*、±8 *g*、±16 *g*	面向需要数字接口的低成本应用	三轴	数字
ADXL362/ADXL363	超低功耗、低带宽	测量设备活动，以进行预防性维护；由电池或者通过能量收集供电	三轴	数字
ADXL372/ADXL375/ADXL377	高度全面缩放/冲击检测	适合冲击检测，以进行纠正性维护	三轴	模拟或数字
ADcmXL3021	高性能、宽带宽 (10 kHz)、低噪声、集成式FFT、多轴	综合CbM模块，包括三个加速度计和相关的信号处理；非常适合预测性维护	三轴	数字
ADIS16228	±20 *g*、集成式FFT、带宽高达5 kHz	综合CbM模块，用于进行预测性维护	三轴	数字

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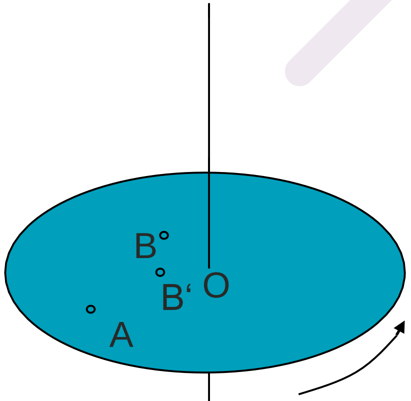
MEMS 陀螺仪

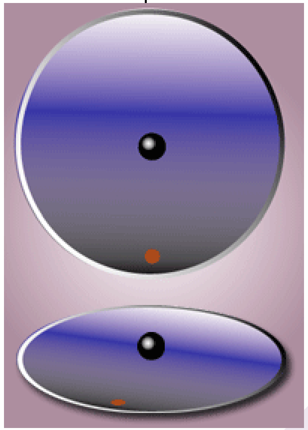
MEMS陀螺仪是怎么工作的?

MEMS陀螺仪工作原理

- 陀螺仪如何测量角速度
  - 通过测量科里奥利力

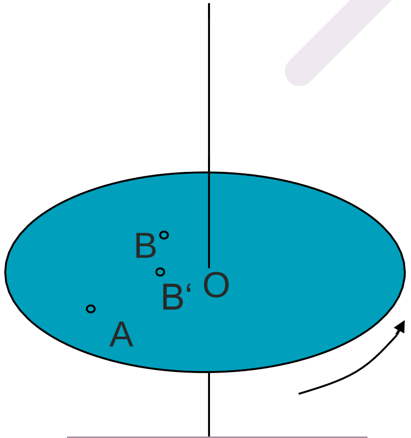
- 什么是科里奥利力
  - 设在以角速度ω沿逆时针方向转动的水平圆盘上，有A，B两点，O为圆盘中心，且有OA>OB，在A点以相对于圆 盘的速度V沿半径方向向B点抛出一球。如果圆盘是静止 的，则经过一段时间：Δt = （OA - OB）/ V后，球会到 达B，但结果是球到达了B转动的前方一点B’，对这个现 象可如下分析，由于圆盘在转动，故球离开A时，除了具 有径向速度V’外，还具有切向速度V_A，而B的切向速度为 V_B，由于B的位置靠近圆心，所以$V_A > V_B$，在垂直于AB 的方向上，球运动得比B远些。这是在盘外不转动的惯性 系观察到的情形。

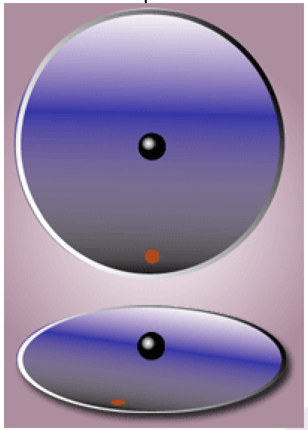




MEMS陀螺仪工作原理

- 什么是科里奥利力
  - 对于以圆盘为参考系的B，他只看到A以初速度向他抛来一球，但球并未沿直线到达他，而是向球运动前方的右侧偏去了，对这一结果的分析发现，球在具有径向初速度V’ 的同时，还具有了垂直于这一方向而向右的加速度a’ ，
  应用牛顿第二定律对于加速度的解释，既然球出手后在水平方向上没有受到“真实力”的作用，那么球一定受到了一个垂直于速度V’ 而向右的惯性力Fc。这种在转动 参考系中观察到的运动物体（由于转动参考系中各点的 线速度不同而产生）的加速现象即为科里奥利效应，产 生此效应的虚拟的惯性力叫科里奥利力。





陀螺仪工作原理

- 科里奥利力公式推导
  - 以转动系为参考系，球从A到B’的时间是

$\triangle t' = (OA-OB)/V'$

在$\triangle t'$时间内，球偏离AB的距离

$BB' = (V_A-V_B)*\triangle t'$

$= \omega*(OA-OB)*\triangle t'$

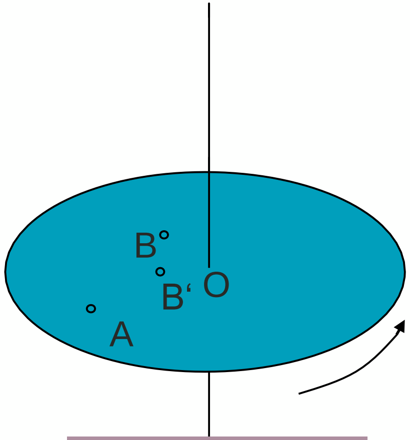
$= \omega*V' * \triangle t' \hat{} 2$

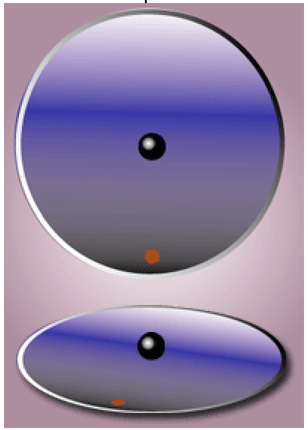
在$\triangle t'$很小的情况下，可以认为沿BB’的运动是匀加速运动而初速为0，则

$BB' = 1/2*a' * \triangle t' \hat{} 2$

与上一结果比较可得：

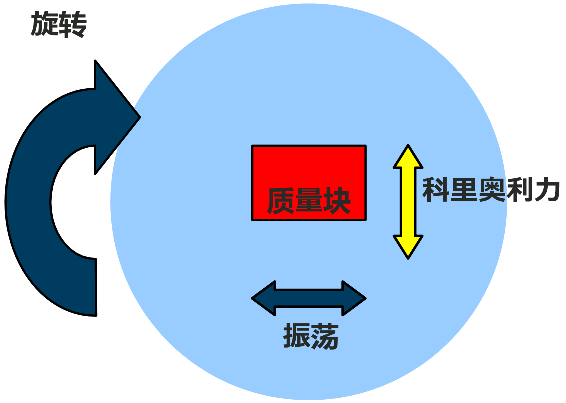
$a' = 2*\omega*V'$



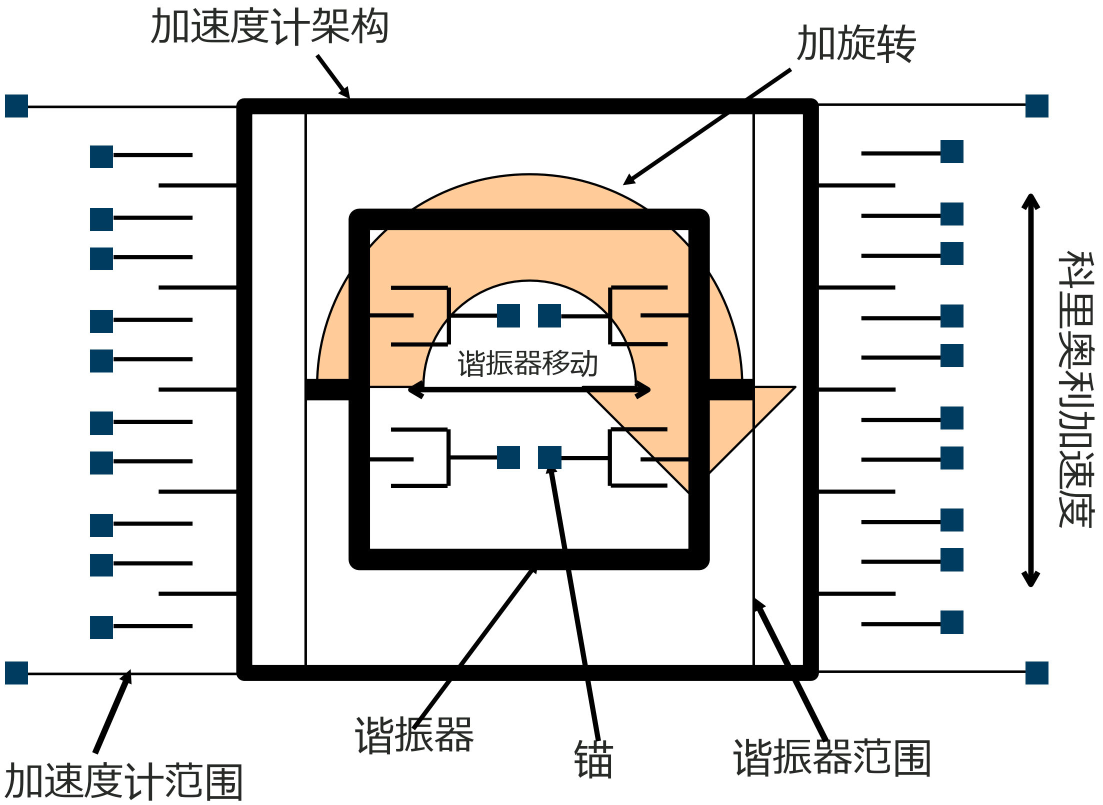


陀螺仪工作原理

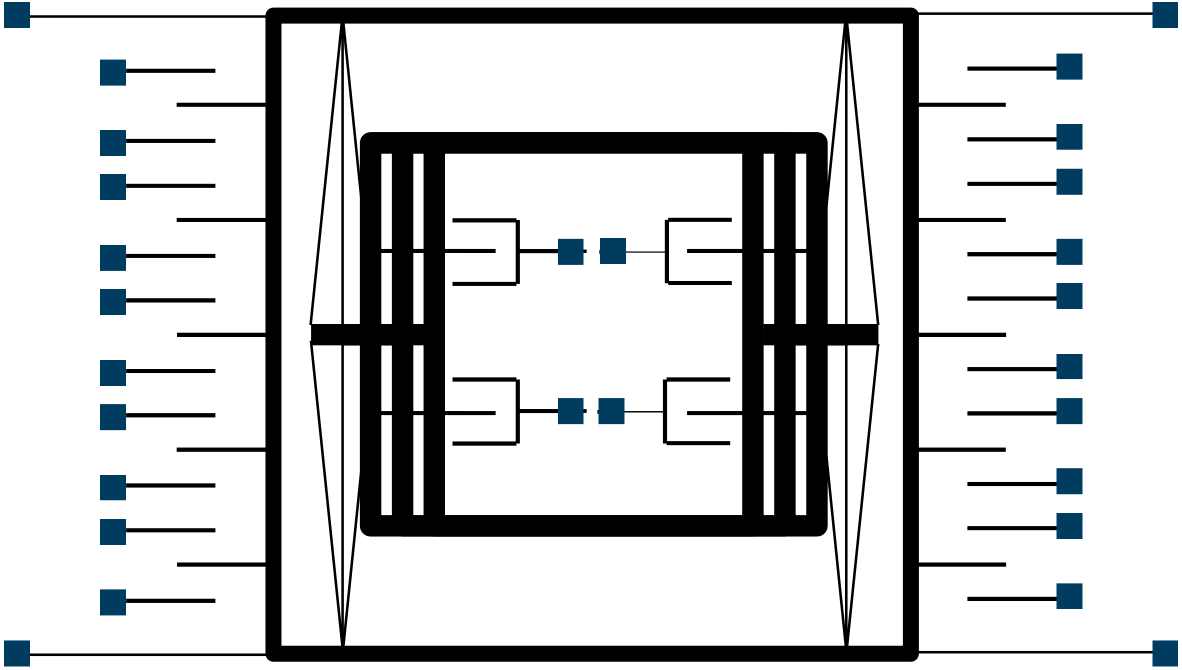
► 当一个物体作周期运动时（振荡或者旋转），在其正交平面内旋转物体，也会在与物体周期运动的垂直方向上产生科里奥利力。



陀螺仪工作原理

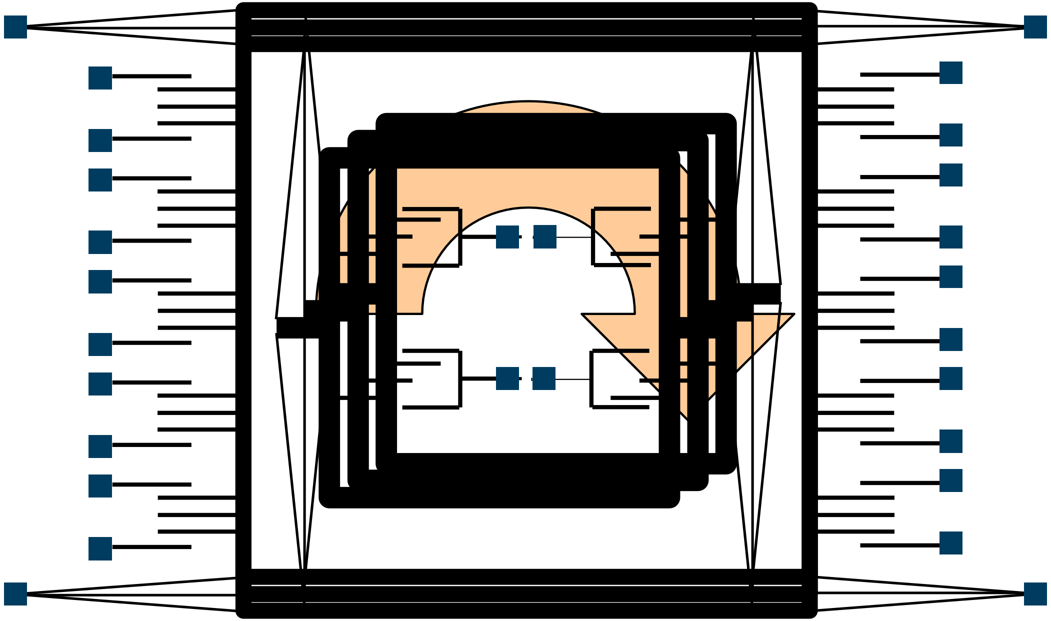


陀螺仪工作原理



没有旋转

陀螺仪工作原理



加旋转

单质量块陀螺仪的问题

- 单质量块陀螺仪不能区分旋转（待测量）和与内部谐振器相同频率的振动
  - 外部的振动会那么容易产生与内部谐振器相同的频率吗?

    答案是肯定的，比如冲击事件，其时域输出是脉冲，相应的频谱成分无限丰富， 此时，单质量块陀螺仪即无法区分该事件和实际的旋转角速度。
- ADXRS系列陀螺仪至少采用两个质量块，它们以相同的频率振荡，但相位相差180°
  - 此时冲击和振荡表现为共模输出，所以采用差分操作可以抑制掉很多误差。

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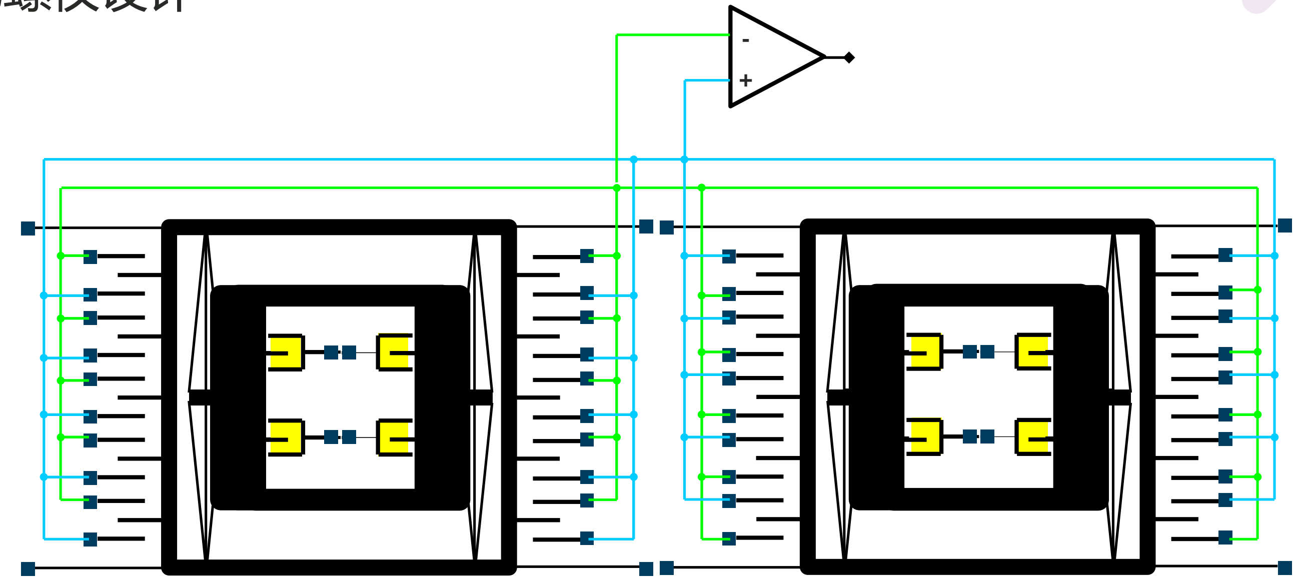
双核陀螺仪

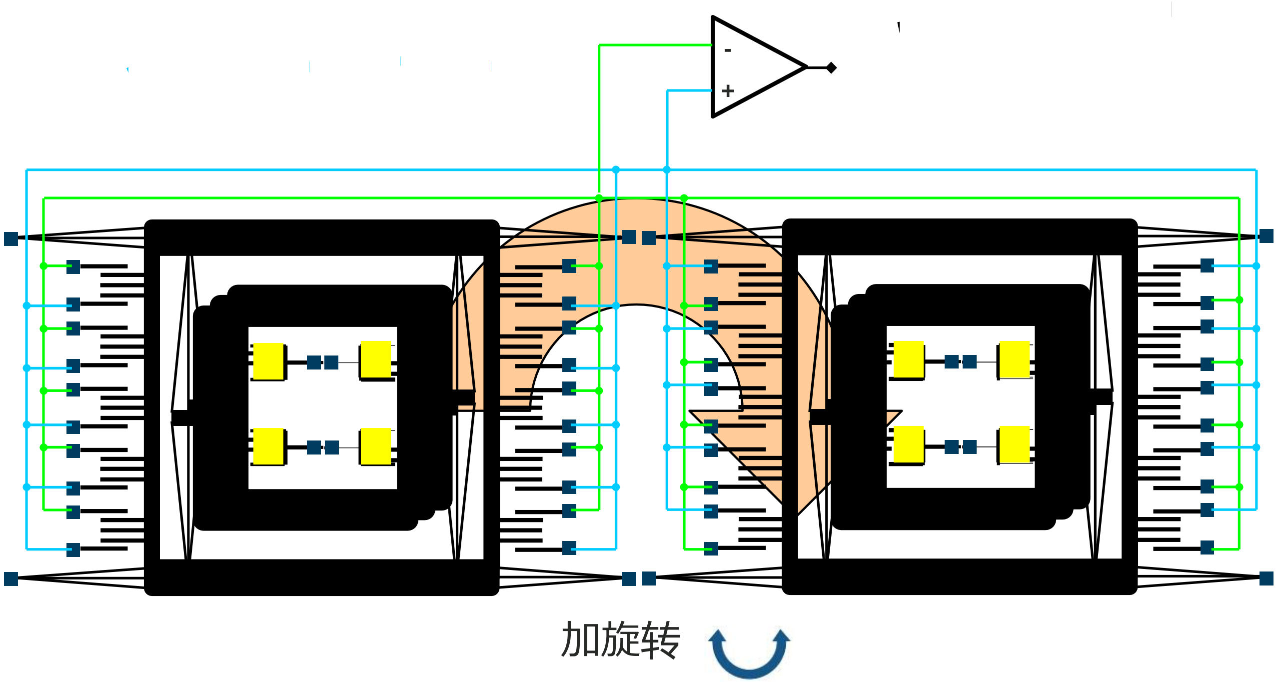
► 双核陀螺仪设计



没有旋转

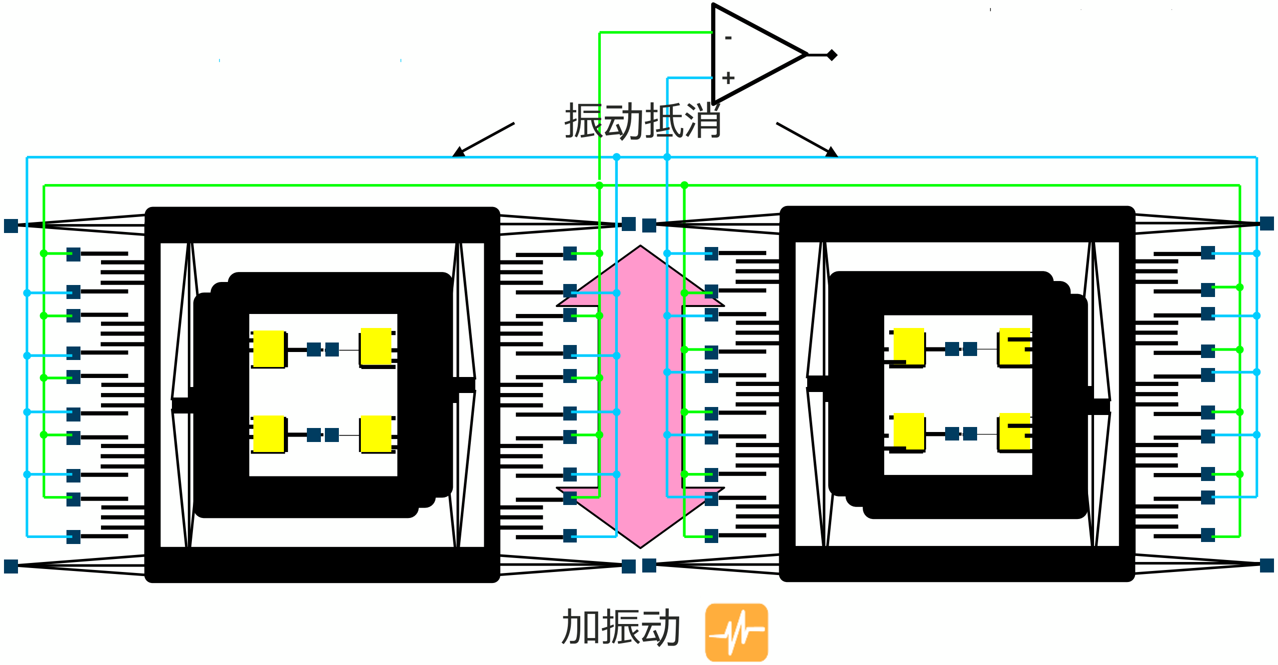
双核陀螺仪

- 双核陀螺仪设计



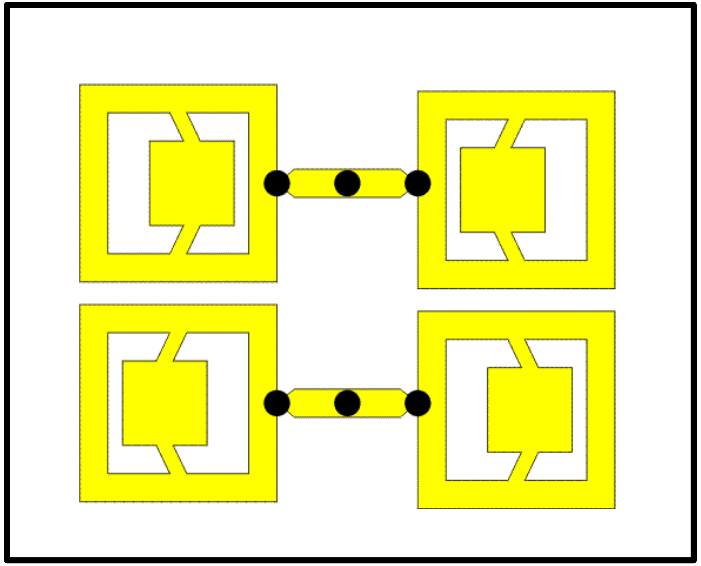
双核陀螺仪

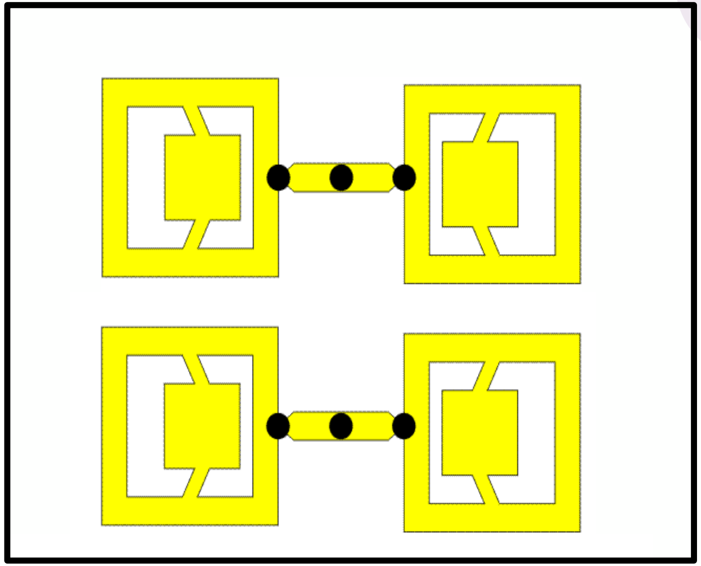
- 双核陀螺仪设计



MEMS陀螺仪工作原理

► 四核陀螺仪设计





加旋转

加振动

陀螺仪的参数 ADIS16495为例

GYROSCOPES					
Dynamic Range	ADIS16495-1BMLZ	±125			°/sec
	ADIS16495-2BMLZ	±450		±480	°/sec
	ADIS16495-3BMLZ	±2000			°/sec
Sensitivity	ADIS16495-1BMLZ, 32-bit		10485760		LSB/°/sec
	ADIS16495-2BMLZ, 32-bit		2621440		LSB/°/sec
	ADIS16495-3BMLZ, 32-bit		655360		LSB/°/sec
Error Over Temperature	$-40°C \le T_C \le +85°C$, 1 σ		0.2		%
Misalignment	Axis to axis		±0.05		Degrees
	Axis to frame (package)			±0.25	Degrees
Nonlinearity[1]	1 σ, ADIS16495-1BMLZ, FS = 125°/sec		0.2		% FS
	1 σ, ADIS16495-2BMLZ, FS = 450°/sec		0.2		% FS
	1 σ, ADIS16495-3BMLZ, FS = 2000°/sec		0.25		% FS
Bias					
In Run Bas Stability	1 σ, ADIS16495-1BMLZ		0.8		°/hr
	1 σ, ADIS16495-2BMLZ		1.6		°/hr
	1 σ, ADIS16495-3BMLZ		3.3		°/hr
Angular Random Walk	1 σ, ADIS16495-1BMLZ		0.09		°/√hr
	1 σ, ADIS16495-2BMLZ		0.1		°/√hr
	1 σ, ADIS16495-3BMLZ		0.18		°/√hr
Error over Temperature	$-40°C \le T_C \le +85°C$, 1 σ		0.1		°/sec
Linear Acceleration Effect	Any axis, 1 σ (CONFIG register, Bit 7 = 1)		0.007		°/sec/*g*

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零偏稳定性与角度随机游走

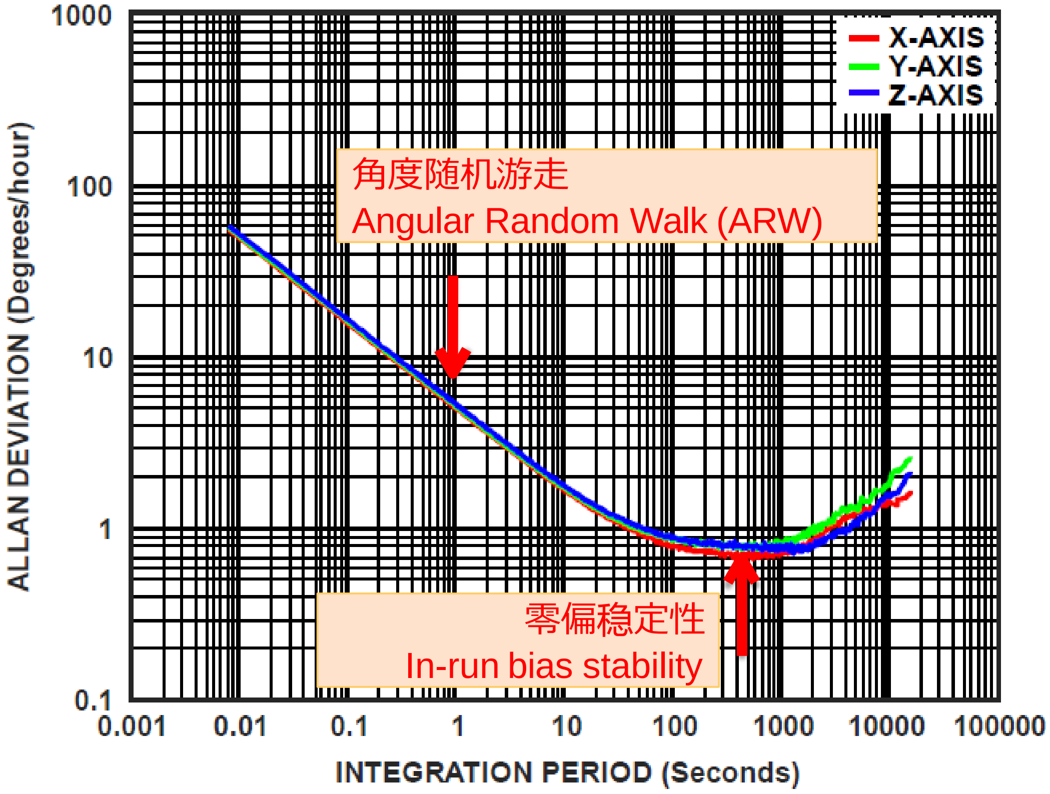


Figure 9. Gyroscope Allan Deviation, ADIS16495-1

抗振动性的重要性　案例说明

误差源	ADI ADXRS 450	ADI ADXR S453	I&I Competitor 1	I&I Competitor 2
零偏稳定性	25°/ hr	16°/ hr	5°/ hr	2°/ hr
振动抑制性能	0.03°/sec/g	0.01°/sec/g	0.1°/sec/g	0.1°/sec/g
振动灵敏度 (假设重力有10°倾角分量)	0.0052°/sec	0.0017°/sec	0.0174°/sec	0.0174°/sec
RSS误差 (°/hr)	31.23	17.13	62.84	62.67

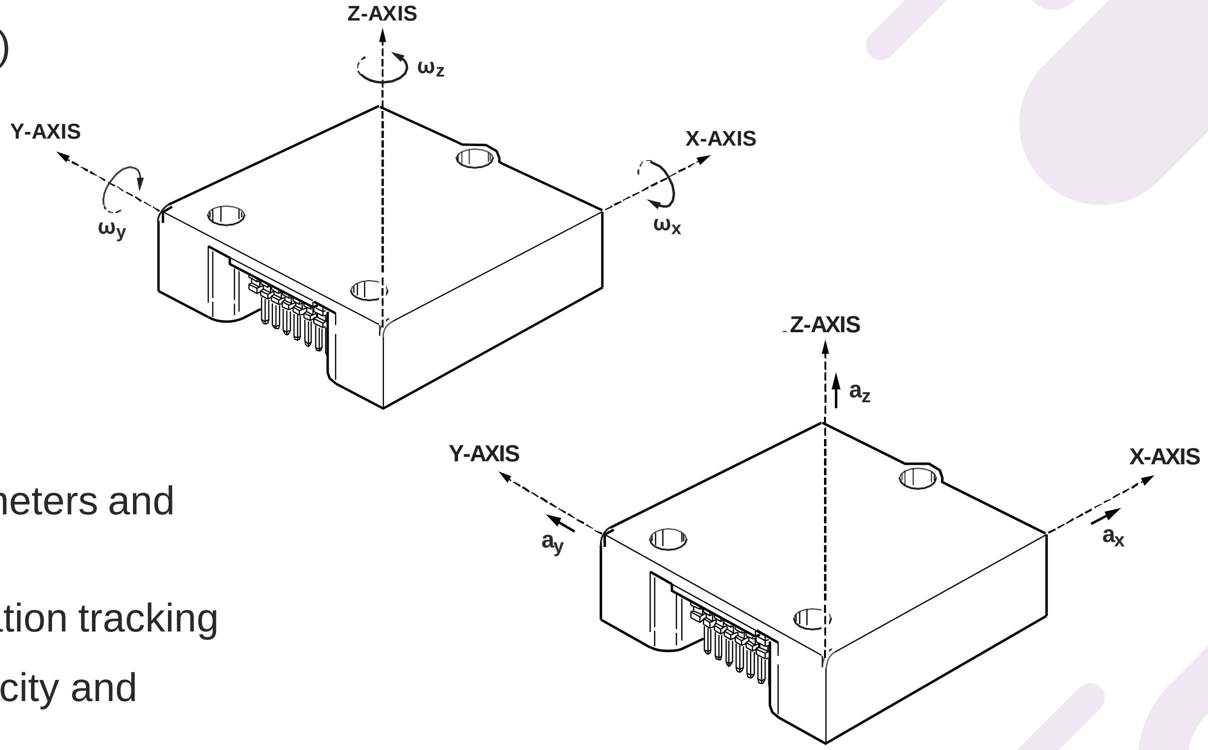
较高的零偏稳定性 + 较低的振动灵敏度 = 较低的系统误差

注意: 振动灵敏度通常是系统里的最大误差源，并且无法校准。

即使增加橡胶等“减震”处理也无法改善重力加速度所带来的影响。

MEMS IMU

- Angular rate of rotation (spin rate)
  - Delta-angle
- Linear acceleration
  - Delta-velocity
  - Orientation, with respect to gravity (aka….tilt, incline angle)
- Triaxial measurements
  - Mutually orthogonal
- Legacy IMUs also had magnetometers and barometers
- Primary use is in dynamic orientation tracking
- Secondary use in short-term velocity and position tracking



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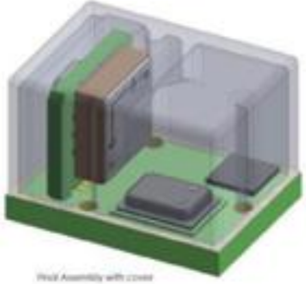
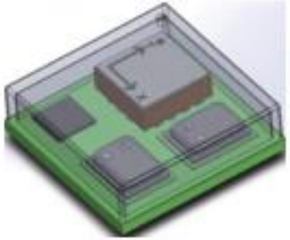
IMU 的外观展示





IMU 指标

- Stability/repeatability (long-term drift; scale and bias)
- Noise (angle random walk)
- Vibration rectification
- Hysteresis

→ Inherent to sensor performance

- Nonlinearity
- *g* effect error (linear acceleration)

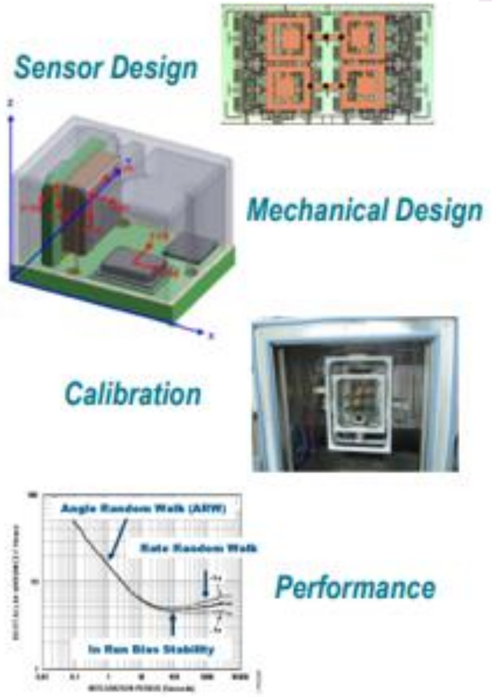
→ Theoretically capable of being corrected through test and calibration

- Offset/bias
- Scale/gain error
- Tempco's
- Cross-axis sensitivity

→ Correctable through test and calibration

MEMS Sensor Level

Calibration Focus

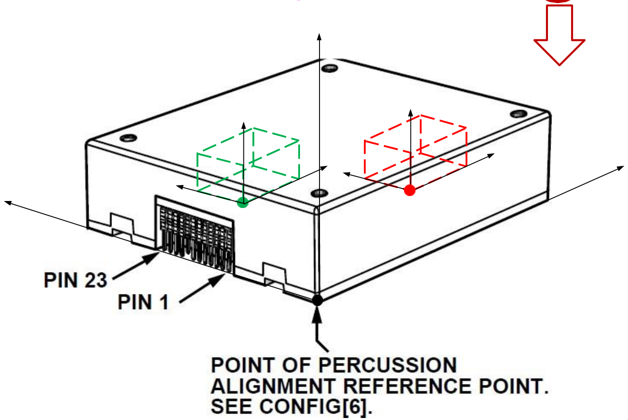


IMU 校准

- Pre-Calibration Accelerometer Output
  - a_X a_Y a_Z
- Post Calibration Accelerometer Output
  - a_{XC} a_{YC} a_{ZC}
- Bias Correction (1)
- Scale Factor Correction (2)
- Alignment Correction Error Correction (2)
- The Point of Percussion Correction (3)
  - Map the accelerometer to the corner of the IMU package
- Temperature Correction (4)

$$\begin{pmatrix} a_{XC}\\ a_{YC}\\ a_{ZC}\end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & m_{13}\\ m_{21} & m_{22} & m_{23}\\ m_{31} & m_{32} & m_{33}\end{pmatrix}\left(\begin{pmatrix}a_X\\ a_Y\\ a_Z\end{pmatrix}+\begin{pmatrix}b_X\\ b_Y\\ b_Z\end{pmatrix}\right)+\begin{pmatrix}0 & p_{12} & p_{13}\\ p_{21} & 0 & p_{23}\\ p_{31} & p_{32} & 0\end{pmatrix}\begin{pmatrix}\omega_{XC}^2\\ \omega_{YC}^2\\ \omega_{ZC}^2\end{pmatrix}$$

2 1 3



IMU 校准

- Pre-Calibration Gyro Output
  - ω_X ω_Y ω_Z
- Post Calibration Gyro Output
  - ω_{XC} ω_{YC} ω_{ZC}

$$\begin{pmatrix} \omega_{XC} \\ \omega_{YC} \\ \omega_{ZC} \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \left(\begin{pmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{pmatrix} + \begin{pmatrix} b_X \\ b_Y \\ b_Z \end{pmatrix} \right) + \begin{pmatrix} l_{11} & l_{12} & l_{13} \\ l_{21} & l_{22} & l_{23} \\ l_{31} & l_{32} & l_{33} \end{pmatrix} \begin{pmatrix} a_{XC} \\ a_{YC} \\ a_{ZC} \end{pmatrix}$$

② ① ③

- Bias Correction (1)
- Scale Factor Correction (2)
- Alignment Correction Error Correction (2)
- Linear Acceleration Correction (3)
  - Liner g correction factors
- Temperature Correction (4)

ADI IMU 在业界地位

ADIS1635x
ADI First to Market with Industrial Targeted IMUs
2007

ADIS1636X
2× Performance Increase; Interface/Footprint Compatible
2009

ADIS1648x
4× Performance Increase; Tactical Grade IMU
Family 2011

ADIS1644x
50% Size Reduction; Interface Compatible; 10 DoF
2012

ADIS1646x
50% Size Reduction; Noise, Stability, and Cost Improvements
2016

ADIS1647x
70% Size Reduction; Smallest/Best-in-Class IMU
2017

ADIS1650x

40% Size Reduction; High Performance Component-Level IMU
2018

AD24501

Automotive Qualified; High Performance Component-Level IMU

- ✓ **First** to market in MEMs
- ✓ **First** to market in industrial IMUs
- ✓ **Leader** in performance density
- ✓ **Leader** in all-condition industrial-grade performance
- ✓ **Proven** commitment, innovation, and value

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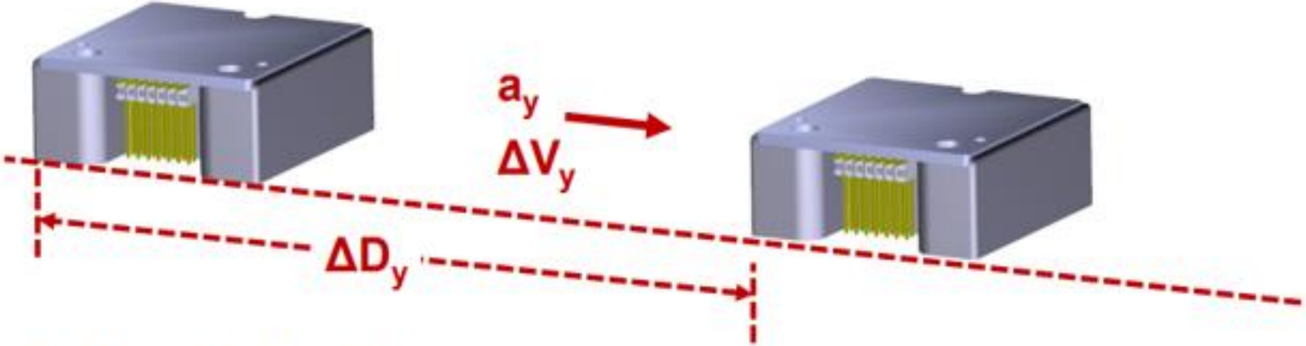
IMU 应用

- 导航与平稳控制

定位原理

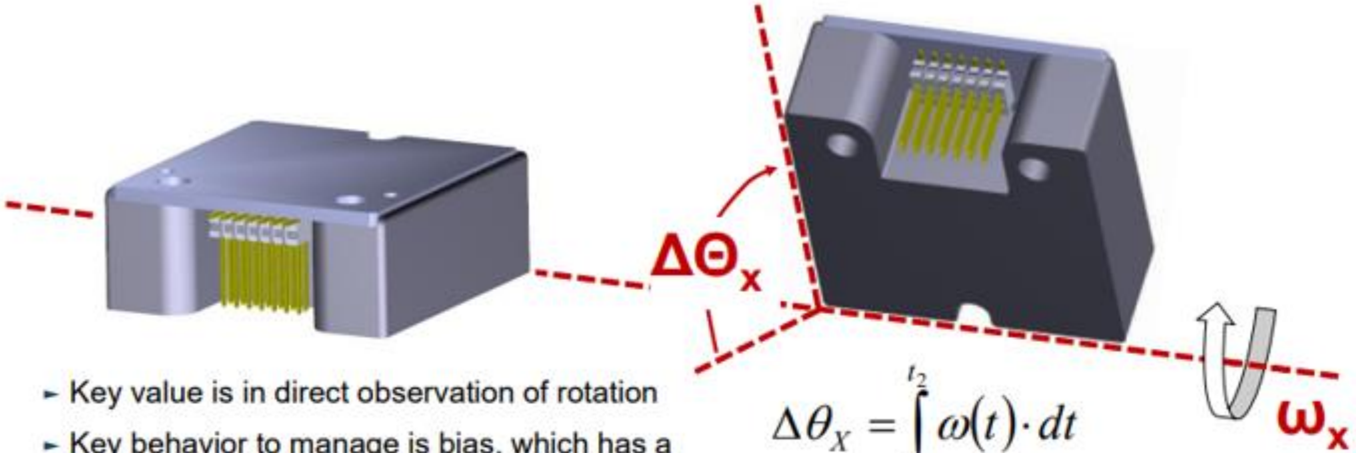


- Delta-velocity registers are available in the ADIS1646x, ADIS1648x products
- Intended to track more short changes, while being augmented by other position tracking "observers"

$$\Delta V_Y = \int_{t_1}^{t_2} a_Y(t) \cdot dt \quad \Delta V_Y = \frac{1}{f_S} \sum_{n=1}^{N} a_Y(n)$$

$$\Delta D_Y = \int_{t_1}^{t_2} \int_{t_1}^{t_2} a_Y(t) \cdot dt^2 \quad \Delta D_Y = \frac{1}{f_S^2} \sum_{n=1}^{N} \sum_{n=1}^{N} a_Y(n)$$

角度测量原理

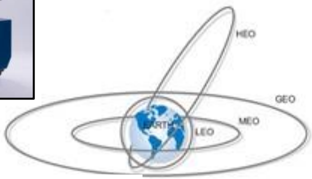


- Key value is in direct observation of rotation
- Key behavior to manage is bias, which has a direct impact on the angle bias drift
- Delta-angle registers are available in the ADIS1646x, ADIS1647x, ADIS1648, ADIS1649x

$$\Delta\theta_X = \int_{t_1}^{t_2} \omega(t) \cdot dt$$

$$\Delta\theta_X = \frac{1}{f_S} \sum_{n=1}^{N} \omega_x(n)$$

应用场景

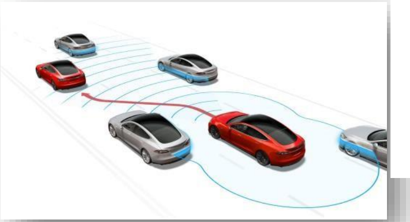






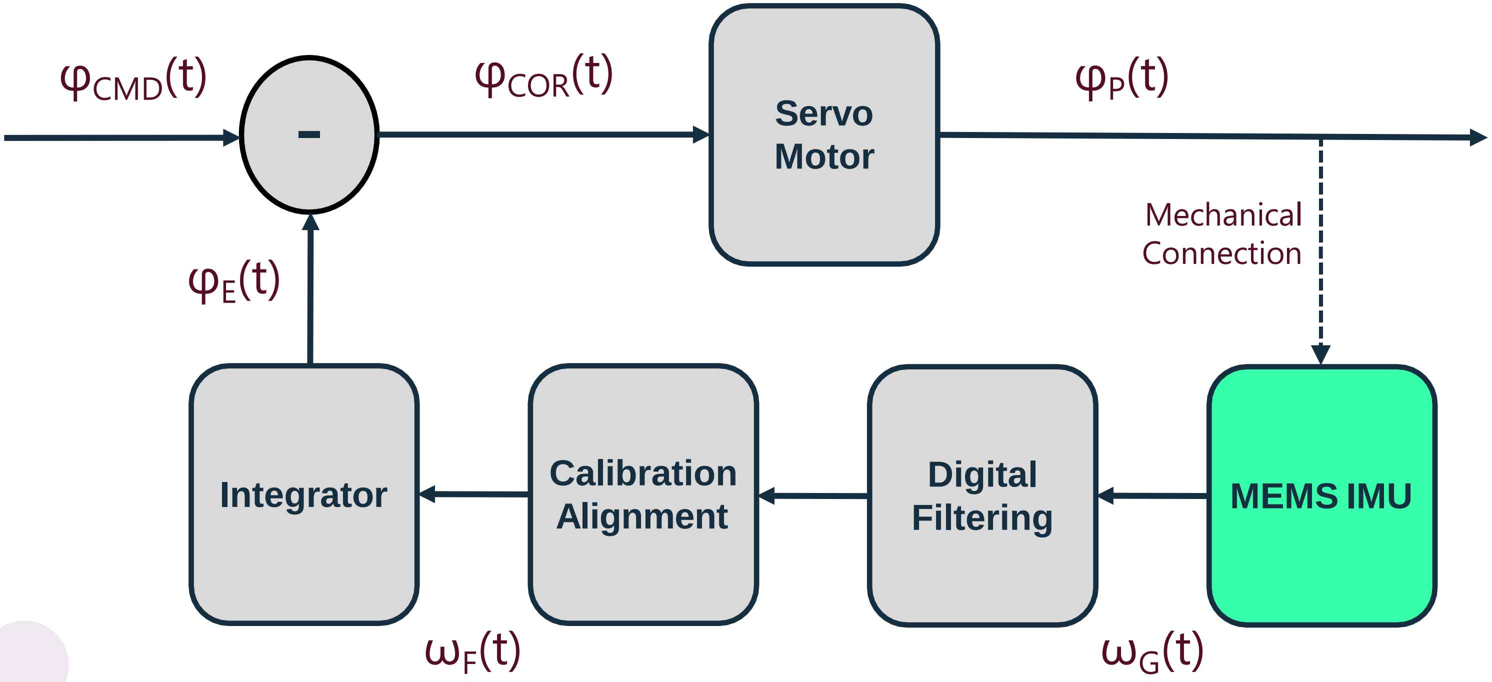
Internet of Moving Things



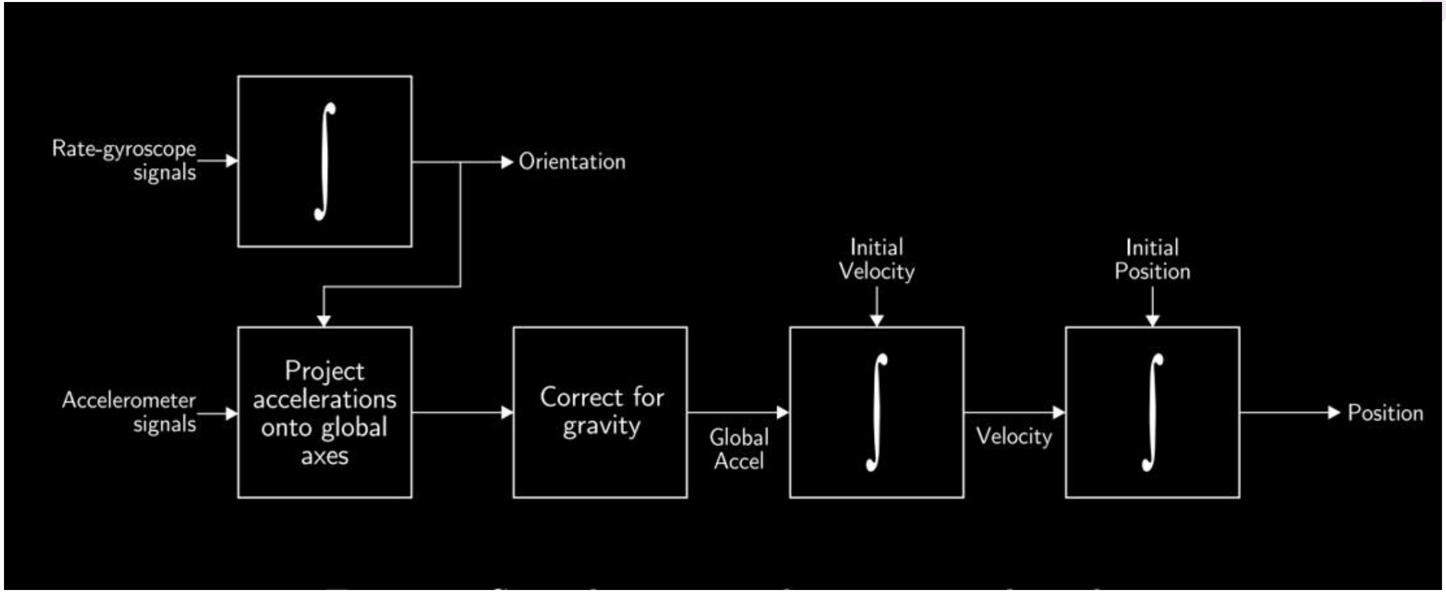



平稳控制原理

平稳控制中的MEMS IMU

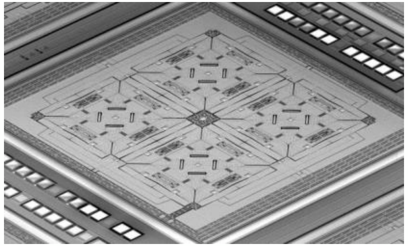


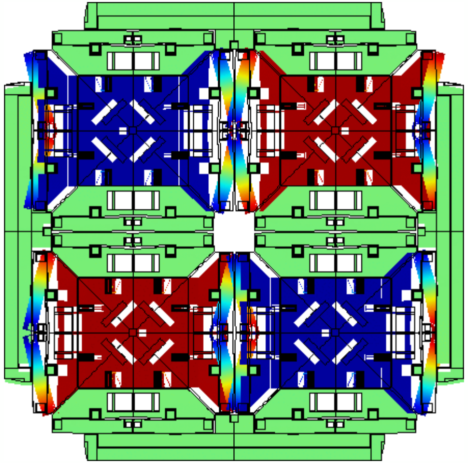
导航应用


Rate-gyroscope signals
∫
Orientation
Accelerometer signals
Project accelerations onto global axes
Correct for gravity
Global Accel
Initial Velocity
∫
Velocity
Initial Position
∫
Position

下一代高性能陀螺仪

- Patent pending couplers allow efficient use of area
- Patented quad mass design to reject vibration
- Fully coupled drive for high Q
- Shuttles to decouple orthogonal forces and motion
- Low stray capacitance for reduced noise
- Patented in-plane quadrature tuning electrodes

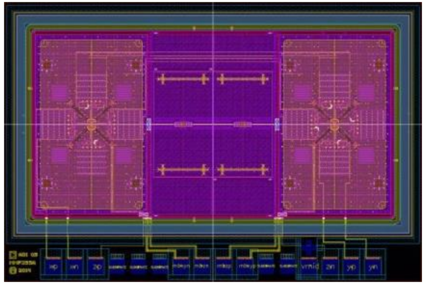




下一代加速度计特点

- Low drift: high stability over life (stress, temperature, moisture, shock, aging, etc.)
- Low noise: ability to resolve low level vibration signals across the frequency band
- Low power: ASIC design innovations; intrinsic

  MEMS design for signal level
- High bandwidth: Condition-based monitoring (bandwidth up to 50 kHz)
- Wide temperature range: the MEMS design delivers guaranteed 0 *g* drift over the entire temperature range



Metric	ADI High Performance Accelerometers	Improvement over Similar Cost Competitors
Noise Density (µg/√Hz)	20	10×
Tempco (m*g*/°C)	0.15	10×
In-Run Stability (µ*g*)	5	10×
Long-Term Bias Repeatability (m*g*)	5	100×
Power/Current (µA)	<2	10× to ~100×

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ADIS1650X 性能对比

Product Features	ADIS1650X	Aceinna IMU330B	Epson V340	Xsens Mti-1	INV MPU6050	Fairchild FIS1100
Dynamic Range (Gyro/Accel)	125 to 2000 dps 8 *g* to 40 *g*	±400°/sec ±8*g*	450 dps 6 *g*	2000 dps 16 *g*	250 to 2000 dps 16 *g*	2560 dps 8 *g*
Gyro In-Run Bias (dph)	2.0	2	3.5	<10		
Gyro Noise, ARW °/s/√Hz, °/√hr	0.003 *0.15*	0.2	0.0025 .17	0.01	0.005	0.01
Bandwidth Hz	550	50	200	180	256	345
Vibration Rejection dps/*g*	0.010	No spec	0.01	(0.001)**	0.1	
Alignment Accuracy (deg)	0.1°	0.01%FSR (?)	0.1°	0.1°	1.1°	1.1°
Bias Tempco dps/°C	0.002	0.004	0.001		0.16	0.1
Accelerometer Noise, VRW mg/√Hz, m/s/√hr	0.023 0.012	0.020	0.25 0.15	0.2	0.4	0.05
Bandwidth Hz	600	50	200	180	260	
Bias Tempco m*g*/°C	0.008	0.046	0.1		0.86	
Temperature Range	–40°C to +105°C	–40°C to +85°C	–40°C to +85°C	–40°C to +85°C	–40°C to +105°C	–40°C to +85°C
Package (in mm)	15 x 15 x 5	11x15x3mm	10 x 12 x 4	12.1 x 12.1 x 2.6	4 x 4 x .95	3.3 x 3.3 x 1

*ADIS16500

**questionable, likely not under same conditions

- Higher priced
- Range, bandwidth, and accel limitations

- Questionable value
- Performance limited

- Lower-cost, but not suitable for performance driven apps
- Order of magnitude lower performance

ADIS16500:
2000 dps, 40 *g*,
(–25 to +85°C)

ADIS16505:
2000 dps, 8 *g*,
–40 to +105°C

ADIS16507:
2000 dps, 40 *g*,
–40 to +105°C

Confidential

IMU参数对性能的影响

Value of IMU is Proportional to Bias Stability Under Actual Operating Conditions (True/Application-Level Bias)

Sensor Grade	Cost	Value to Sensor Fusion
Low Precision Consumer Sensors	$	nil, 'along for the ride'
ADI Indus/Tac Grade Sensors	$$	Primary Sensor during tens-of-seconds outages, state-transitions, blindness…
Military/Nav Grade Sensors	$$$$$	Potential to be the only sensor in some cases, (cost-prohib)

Relative Performance Measures

error in meters

Achievable Bias (incl all errors)	~error, 30 s, 30 mph	~error, 60 s, 30 mph
10 dph	2.2 m	17.3 m
5 dph	1.1 m	8.6 m
1 dph	0.2 m	2.7 m
0.1 dph	0.1 m	0.3 m

Not all 1-dph are the same…

in-run bias (dph)	10		5			1			
linear-g (dps/g)	*0.1*	*0.05*	*0.1*	*0.05*	*0.01*	*0.1*	*0.05*	*0.01*	*0.001*
linear-g effect under 5deg tilt (dph)	31.4	15.7	31.4	15.7	3.1	31.4	15.7	3.1	0.3
Total/Actual Bias (dph)	**33**	**18.6**	**32**	**16.5**	**5.9**	**31.4**	**15.7**	**3.25**	**1.04**

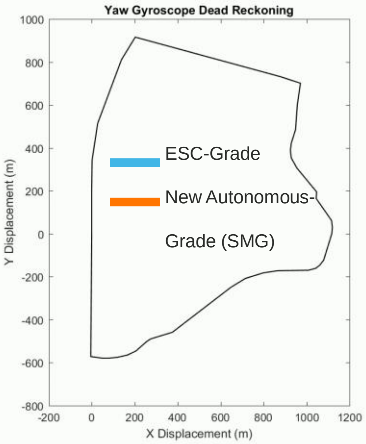
Comp-C Comp-B Comp-A ADI

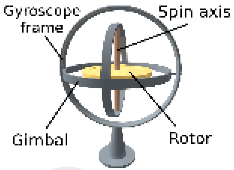
For example, a 1 dph gyro with poor (0.1) *g*-rejection is equivalent to a >30 dph gyro when experiencing minimal tilt (road grade, tire pressure differences, …)

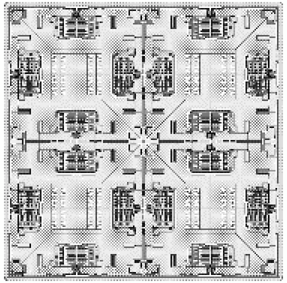
IMU 实测案例

Gyro Offset, Short and Long Term…
… Key to Providing Value in Sensor Fused Navigation System

- Single Axis Gyro Integrated
- Velocity from OBD2 port
- 3 Loops: 2.8 mile and 7 minutes, per loop
- Simple, non-optimized test demonstrating significance of bias stability
  - Initial offset subtracted

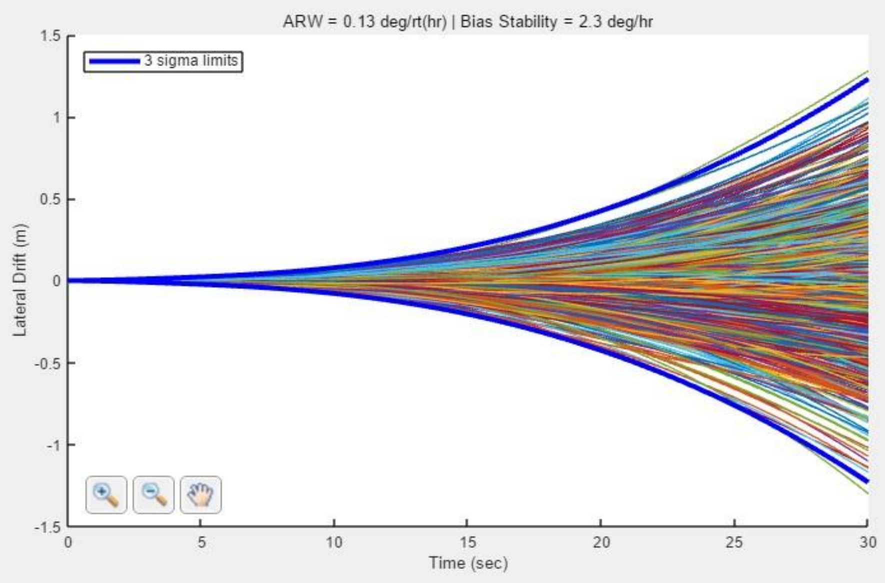






Gyro Spec	Cell Phone Sensors	Typical ESC Grade	Expected Autonomous Grade	Implication / Advantage
Bias stability	> 15 °/hr (unbalanced, uncharacterized, typically not specified)	10°/hr	<1 °/hr	Tactical Grade Stability, Substantially Reduced Position Error

ADIS1650X 性能分析



- Car Velocity
  - 100km/h
- Road Vibration
  - 1g rms
- IMU SPEC
  - ARW=0.13 d/rtHr
  - IRBS=2.3dph
  - Linear g rejection 0.01dps/g
- Simulation Results
  - The expected lateral drift after travelling at 100 km/hr for 30 seconds is 0.4m (1 sigma). In other words, 68% of the time this gyroscope will have <=0.4m of error after 30s of driving.
  - This gyro can navigate for 17.4s seconds before exceeding 0.3m of lateral error (3 sigma). In other words, 99.7% of the time the error after 17.4s seconds will be less than 0.3m.

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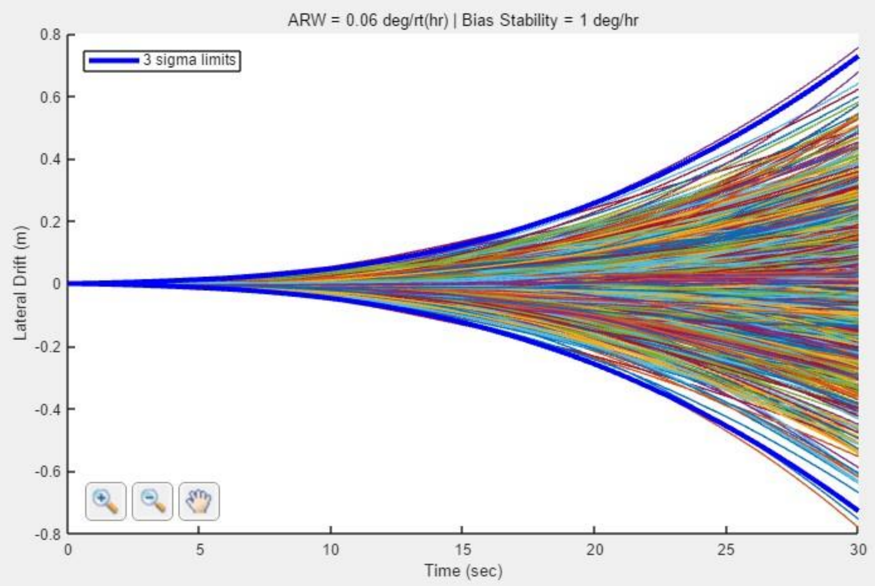
ADIS16495 性能分析



- Car Velocity
  - 100km/h
- Road Vibration
  - 1g rms
- IMU SPEC
  - ARW=0.06 d/rtHr
  - IRBS=1dph
  - Linear g rejection 0.01dps/g
- Simulation Results
  - The expected lateral drift after travelling at 100 km/hr for 30 seconds is 0.2m (1 sigma). In other words, 68% of the time this gyroscope will have <=0.2m of error after 30s of driving.
  - This gyro can navigate for 21.2s seconds before exceeding 0.3m of lateral error (3 sigma). In other words, 99.7% of the time the error after 21.2s seconds will be less than 0.3m.

IMU 推荐与Roadmap

Available Component and Module Inertial Solutions for High Performance Applications

- **Low noise, low drift, vibration rejecting gyroscopes**
  - ADXRS290/5, dual axis
  - ADXRS646, single axis
  - ADXRS62X, 453 lower performance, cost
- **Low noise, low drift accelerometers**
  - ADXL35X, tri axis
  - ADXL203, dual axis
  - ADXL34X, 350: lower performance, cost
- **Six DoF inertial measurement units**
  - ADIS1649X,485 tactical grade performance
  - ADIS1646X/47X, best size/cost
  - ADIS16445 cost/performance
- **Ten DoF inertial measurement units**
  - ADIS16448 cost/performance
  - ADIS16488 highest performance
- **Vibration/HUMs/shock sensors**
  - ADXL100X, single-axis, ultra low noise
  - ADIS16228, tri-axis, integrated FFT
  - ADXL372, tri-axis, high-*g*, ultralow noise/power
- **AHRS**
  - ADIS16480, attitude and heading outputs
- **Tilt sensors**
  - ADIS16209, dual-axis precision inclination
  - ADIS16210, tri-axis precision inclination
- **Motion activation/monitoring**
  - ADXL362, tri-axis ultra low power acceleration/switch

高性能低成本 ADIS1650X ADIS1647X

ADIS1650X and ADIS1647X

- High end module performance in small, cost-effective complete solution
  - 2°/hr
- Robust sensing measurements reduce the need for complex isolation or system-level compensation
  - Industry best g-rejection and alignment
- System ready implementation through proven *i*Sensor integration, calibration, and reliability

Key Benefits

- Wide dynamic range (2000 dps, 40 *g*) coupled with low noise, low drift, and high vibration immunity, for the most accurate sensing under complex motion
- Integration and precision alignment of industrial-grade linear and rotational sensing cores into complete IMU with optimized embedded sensor processing
- Calibration across temperature on every device ensures best possible performance and lower overall system cost

Portfolio Positioning

- 70% size reduction over prior generations
- Lowest noise industrial-grade IMU
- Targeted at high volume (cost-sensitive) industrial applications, which demand and value high performance

Industry Positioning

- Only industrial-grade IMU in surface mount package
- 5× wider dynamic range and 2× wider bandwidth than existing modules
- Up to 10× better vibration rejection
- Up to 10× lower accelerometer noise

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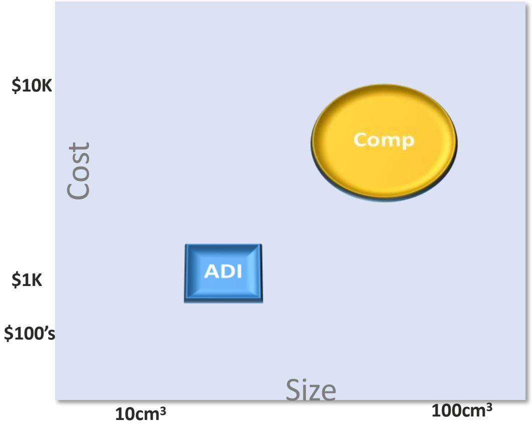
高性能 IMU

ADIS16490/ADIS16495/ADIS16497 Inertial Measurement Units
Tactical Grade, Highly Stable, and Ultralow Noise

- Tactical-grade performance
  - Noise: 1.6 mdps/√Hz; 16 μg/√Hz
  - In-run bias: 0.8°/hr; 3.6 μg
- Lowest noise linear and rate sensors
- Industry best vibration rejection
- System ready implementation through proven *i*Sensor integration, calibration, and reliability



Key Benefits

- Low drift navigation and low jitter stabilization in extreme/complex environments
- Calibration, across temperature, on every device ensures critical performance and dynamic compensation
- Integration and precision alignment of tactical-grade linear and rotational sensing cores into complete sensor-fused IMU, with optimized embedded sensor processing
- Footprint and interface-compatible with ADIS1648x generation *i*Sensor IMUs



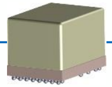


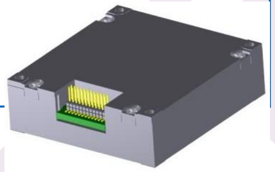
Industry Best SWaP/$

包装对比

ADIS1646x/ADIS1647x/ADIS1649x:

	ADIS1646x	ADIS1647x	ADIS1649X
Size	24.3 × 22.4 × 9 mm	15 × 11 × 15 mm	44 × 47 × 14 mm
Solder-reflow attach?	NO Requires post fab install	YES 44-ball BGA Single-pass PCB fab	NO Requires post fab install
Connector?	YES 14-pin Flexibility in PCB fab	NO Limitations on PCB fab	YES 22-pin Flexibility in PCB fab
Keyed Connector?	NO Easier to insert incorrectly	NO	YES Reduced mis-insertion risk
Precision alignment features?	NO 1° (typical)	NO >1° (typical)	YES 0.25° (max)





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Roadmap

Inertial Measurement Unit (IMU) Roadmap

IMU

High Performance

- **ADIS1648x** 5 dph *
- **ADIS1649x** <2 dph
- **Reagan** <1 dph
- **Kennedy** Tactical-Grade Repeatability
- **Truman** <1 dph

Leading Short-term Stability … Leading Long Term Repeatability

Compact Performance

- **ADIS1644x** 10cm³ 12 dph
- **ADIS1646x/ ADIS164 7X** <5 dph
- **FALCON** <5 dph
- **KITE** <5 dph
- **RAPTOR** 0.25 cm³ <5 dph

Industrial IMU Market Leader … Component Level HighPerf IMU

Zeus 1 and Zeus 2 AutoQual

Component/Core

- **Quad-Mass/ Solitude** – Industry Best Total Specification
- **ADXL35x** <5 *mg* Repeatability – Ultralow Noise, 3-Axis Accelerometer
- **XRS295/SMG** – Tactical Grade
- **PRYM** <5 dph – Multi-axis

2017	2018	2019	2021 to 2023

*: Flight certified; DAL-B Design Assurance, DO-178/DO-254 Certification Artifacts