Experimental Validation of the Dynamic Inertia Measurement Method to find the Mass Properties of an Iron Bird Test Article

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Introduction/ Motivation

Mass Properties

- **Necessary to understand and control the flight dynamics of the vehicle.**
  - mass
  - center of gravity (CG)
  - moments of inertia (MOIs)
  - products of inertia (POIs)
- **Methods to determine mass properties:**
  - **Analytical models** are typically used to determine initial estimates of all mass properties. However, these models must be sufficiently detailed as a realistic representation of the system be accurate.
  - **Weight and balance** procedures are typically used to determine mass and CG information
  - **Spin-balance tables** can provide accurate approximations of all mass properties, but become increasingly difficult to use as the test article size increases.
  - **Swing Tests** use pendulum-based methods. However, pendulum-based methods require significant amounts of labor, materials, and time, leading to high costs and risk to the vehicle and schedule.
  - **Frequency response function (FRF)** testing analyzes the dynamic response of a test article and is often used to identify mode shapes and natural frequencies of objects. The Dynamic Inertia Measurement (DIM) method utilizes FRF information to determine mass properties.

Dynamic Inertia Measurement (DIM) Method

- The mass properties of an object are determined by measuring all forces and moments acting on a body and the rigid body motion caused by these forces and moments.
- The DIM method measures the inertia properties of an object by analyzing the frequency response functions measured during a ground vibration test (GVT).
- The DIM method has been in development at the University of Cincinnati and has shown success on a variety of small scale test articles such as automobile brake rotors, steel blocks, and other custom fixtures from the university

Equations

The DIM method uses the rigid body forces, moments, and linear and angular accelerations to calculate the inertia matrix. Equation 1 shows Newton's second law simplified for constant mass which defines the relationship between forces, mass, and linear accelerations

$$\{F\} = [M]\{\ddot{x}\} \tag{1}$$

Equation 2 shows Euler's second law for defining the relationship between moments, moments and products of inertia, and angular accelerations. For this solution, the cross terms were ignored because the test articles are assumed to be rigid to an extent that the vehicle rotation rate terms were small. Note that this assumption would not hold for large, flexible structures.

$$\{N\} = [I]\{\ddot{\theta}\} \tag{2}$$

Applying the small angle assumption to the moment arms and combining the force and moment equations for six degrees of freedom yields the 6x6 mass matrix for full rigid body motion as shown in Equation 3.

$$\begin{Bmatrix} F_x \\ F_y \\ F_z \\ N_x \\ N_y \\ N_z \end{Bmatrix} = \begin{bmatrix} m & 0 & 0 & 0 & mZ_{CG} & -mY_{CG} \\ 0 & m & 0 & -mZ_{CG} & 0 & mX_{CG} \\ 0 & 0 & m & mY_{CG} & -mX_{CG} & 0 \\ 0 & -mZ_{CG} & mY_{CG} & I_{xx} & -I_{xy} & -I_{xz} \\ mZ_{CG} & 0 & -mX_{CG} & -I_{xy} & I_{yy} & -I_{yz} \\ -mY_{CG} & mX_{CG} & 0 & -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix} \begin{Bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \\ \ddot{\theta}_x \\ \ddot{\theta}_y \\ \ddot{\theta}_z \end{Bmatrix} \tag{3}$$

Previous DIM Method Efforts at AFRC

X-38 Crew Return Vehicle, 1998

First Iron Bird, 2010

GVT Set-up

Purpose

- Ground vibration tests are necessary to assure the aeroelastic stability of new or modified aircraft by determining structural mode shapes

Required Equipment

- Electrodynamic shakers are used to excite the structure at known forces and frequencies
- Single axis accelerometers installed throughout the vehicle measure the structural response
- A soft support system supports the vehicle to simulate free motion and minimize boundary condition effects

DIM Set-Up

- Similar set-up to GVT with addition of 6-DOF force sensors
- All forces, moments, and accelerations are measured quantities.
- The forces and moments are measured from DIM-related 6-DOF force sensors and shaker input sensors. The accelerations are measured from GVT sensors.
- The ten unknown terms in the mass matrix (M) are the mass (m), CG location (X_{CG}, Y_{CG}, Z_{CG}) with respect to some point P, moments of inertia (I_{xx}, I_{yy}, I_{zz}) calculated about P, and products of inertia (I_{xy}, I_{xz}, I_{yz}) calculated about P.

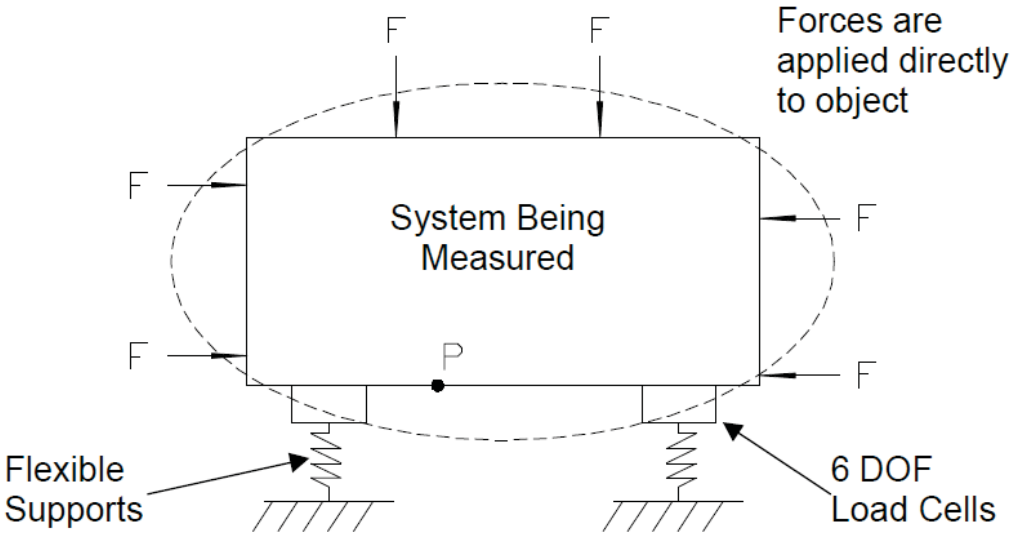
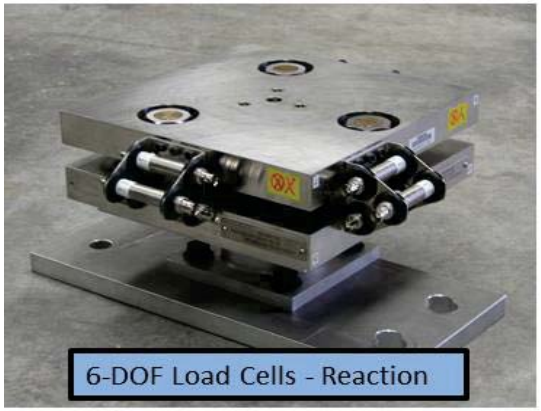
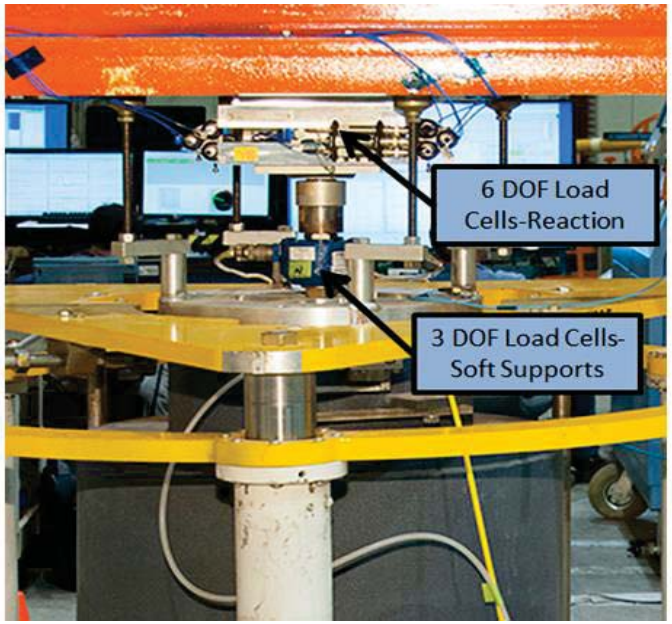


Figure courtesy of :
Witter, M. C., "Rigid Body Inertia Property Estimation Using the Dynamic Inertia Method, Master of Science thesis, Department of Mechanical Engineering, University of Cincinnati, Ohio, 2000.

6-DOF Force Sensors

- Three 6-DOF force sensors were custom-made for the NASA AFRC researchers by PCB Piezotronics, Inc. (Depew, New York).
- These unique sensors are an assembly of three 3-DOF piezoelectric dynamic force sensors. The force sensors were placed between the iron bird and the soft-support system.





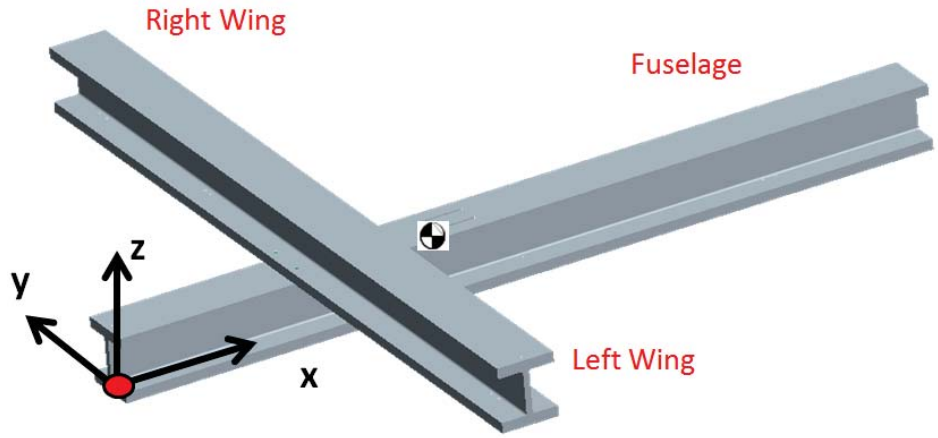
Test Article

- Two 8500-lb 20-foot long, W14x426 steel I-beams were bolted together off-center to model the approximate mass of fighter-type aircraft.
- Since the test article was somewhat visually similar to an aircraft, it was named the “iron bird”.

Analytical Model

- Pro/ENGINEER® was used to analytically model the iron bird test article and obtain the mass properties. Care was taken to apply as many realistic details to the CAD model as possible including all holes and adding interface attachments in order to ensure accuracy. The simplicity of the iron bird test article design was to ensure the analytical CAD model could be treated as the "truth model." The analytic mass properties of the iron bird from the CAD model are shown below.

Mass, lb	$X_{CG,}$ in	$Y_{CG,}$ in	$Z_{CG,}$ in	Ixx, $lb*in^2$	Iyy, $lb*in^2$	Izz, $lb*in^2$	Ixy, $lb*in^2$	Ixz, $(lb*in^2)$	Iyz, $lb*in^2$
17012	90.0	0.0	18.7	$4.34x10^7$	$5.88x10^7$	$9.74 x10^7$	0.0	$-4.78 x10^6$	0.0

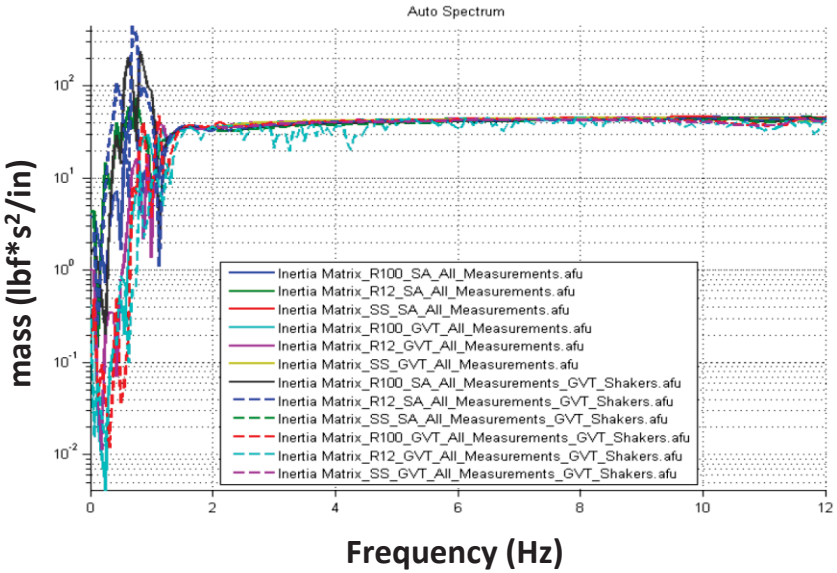


Swing Testing

- Classical pendulum equations were used to determine the moments of inertia
- The moments of inertia about the x-axis and y-axis used a compound pendulum setup
- The z-axis MOI and Ixz POI used a bifilar torsional pendulum setup
- All tests required swinging the fixture by itself in order to subtract out the fixture mass properties from the total combined iron bird and fixture assembly.

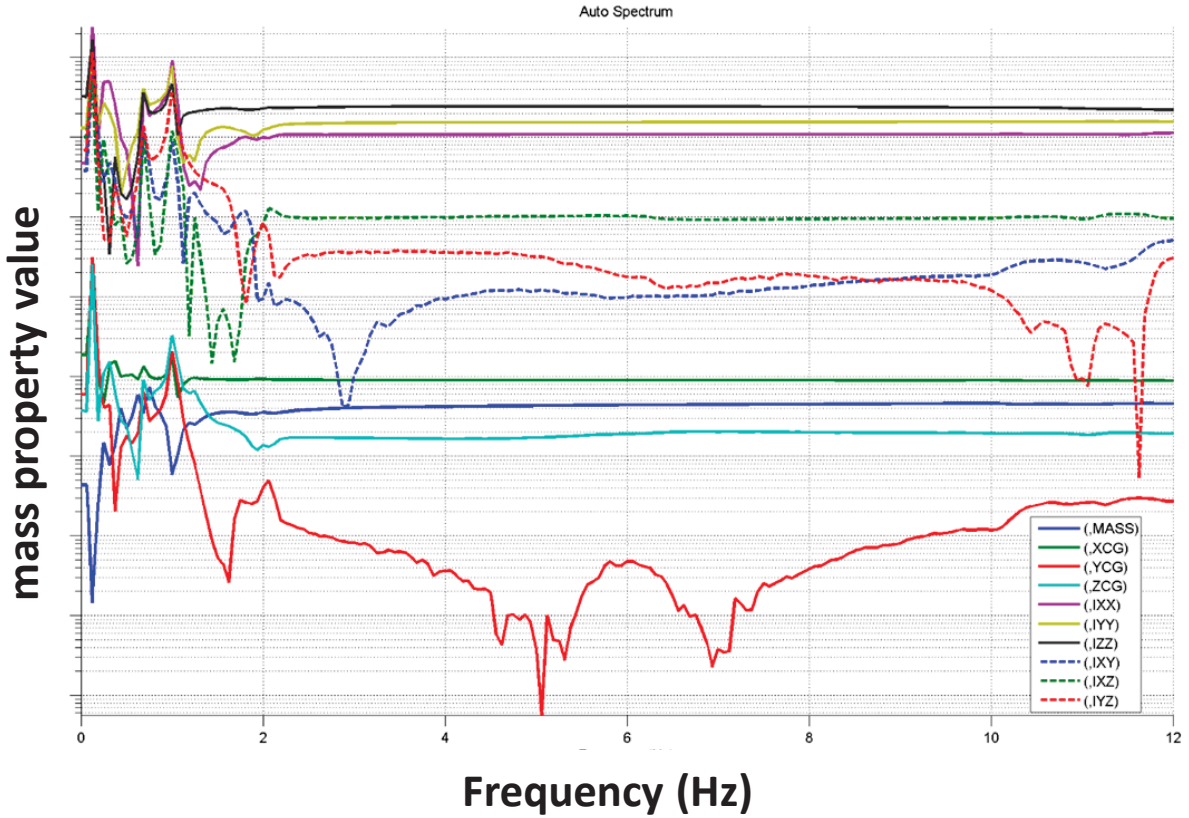
DIM Testing

- The iron bird DIM testing was conducted at the NASA AFRC Flight Loads Laboratory (FLL) from September 16, 2013 through September 24, 2013. ATA Engineering, Inc. (San Diego, California) was contracted to assist with the iron bird DIM testing and to perform analysis of the data
- A total of twelve different DIM analysis cases were conducted through the course of 54 test runs. These runs included check-out, single-shaker, multi-shaker, and quiescent runs.
- Both GVT and seismic accelerometers were used to determine whether higher sensitivity seismic accelerometers are required



Results

- The computed mass, MOI, POI, and CG values are plotted as a function of frequency for DIM analysis case 1 for a 2- to 12-Hz DIM analysis. The mass, XCG and ZCG, three MOIs, and Ixz functions are relatively flat from 2 Hz to 12 Hz. The YCG, Ixy, and Iyz functions exhibit greater fluctuations, but since these values are nominally zero and the estimated values are very small compared to the other CG and POI values, these fluctuations are to be expected.



Results

The DIM method yielded results that matched within approximately 5 percent of the analytical iron bird mass, CG, and MOI. The I_{xz} POI did not match as well, having with errors exceeding 20 percent, however, the DIM I_{xz} results were still better than the 98-percent error from the pendulum-based testing results due to test setup limitations (that is, shallow tilt angle).

Mass, lbm	Mass, error	X_{CG}, in	X_{CG}, % error	Y_{CG}, in	Y_{CG}, % error	Z_{CG}, in	Z_{CG}, % error	I_{XX}, lbm-in^2 x10^7	I_{XX}, % error	I_{YY}, lbm-in^2 x10^7	I_{YY}, % error	I_{ZZ}, lbm-in^2 x10^7	I_{ZZ}, % error	I_{XZ}, lbm-in^2 x10^6	I_{XZ}, % error
Analytical															
17012	-	90.00	-	0.00	-	18.69	-	4.34	-	5.88	-	9.74	-	-4.78	-
Pendulum swing															
16973	-0.2%	90.02	0%	-0.03	0%	18.69	0%	4.19	-3.5%	6.13	4.3%	9.52	-2.3%	-9.46	-97.9%
Dynamic Inertia Measurement															
16805	-1.2%	89.70	-0.3%	-0.20	-	18.20	-2.6%	4.20	-3.2%	5.97	1.5%	9.23	-5.2%	-3.83	19.9%

Timeline Comparison

Pendulum Tests

Activity	Duration, days	Days, specific						Labor	
		5	10	15	20	25	30	Mechanics	Engineers
MOI Setup and fixture build	10							M M M	E
Testing									
Weight and CG test	4							M M M M	E E
I_{xx}	3							M M M M	E E E
I_{yy}	3							M M M M	E E E
I_{zz}	4							M M M M	E E E
I_{xz}	4							M M M M	E E E
Teardown	2							M M M M	

DIM Method Tests

Activity	Duration, days	Days, specific						Labor	
		5	10	15	20	25	30	Mechanics	Engineers
Setup	6							M M M M	E E
Testing	5							M M M M	E E E
Teardown	4							M M M M	E E

Cost Comparison

Cost structure	
$	$1-$100
$$	$101-$1000
$$$	$1001-$10000
$$$$	$10001-$100000
$$$$$	$100001+

Pendulum Tests

One-time cost		Recurring costs	
Laser tracker	$$$$$	Recalibrate load cells	$$$
Swing structure	$$$$$	Swing structure assembly	$$
Test hardware	$$$	Hardware load test	$$
Load cells	$$$		
IMU (optional)	$$$		

DIM Method Tests

One-time costs			Recurring Costs (per year)		
GVT Equipment	DACS	$$$$$	GVT	Recalibrate Accels & Force Transducers	$$$
	Soft Supports	$$$$		Soft Support Maintenance	$$$
	Accelerometers	$$$$		Software Maintenance	$$$
	Shakers	$$$		Recalibrate 6-DOFs	$$$$
	Force Transducers	$$$			
	Software licenses	$$$			
	Wiring	$$$			
	Laser tracker	$$$$$			
	6-DOF Force sensors	$$$$			
	Seismic Accels	$$$			

Conclusions and Lessons Learned

- The Dynamic Inertia Measurement (DIM) method shows promise for mass properties testing applications involving large aerospace vehicles.
- There were sources of error that required mitigation; for example, the soft-support system introduced modes into the test data.
- The DIM method was found to be sensitive to different shaker configurations and test setups.
- Performing the DIM method on the “iron bird” test article advanced the maturity level of the method toward future use on full-scale aerospace vehicles. The next step in the maturation of the DIM method would be to apply the technique to a full-scale aerospace vehicle.

Acknowledgements

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Questions?

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