APPLICATION OF SEMICONDUCTOR STRAIN GAUGES IN MEASUREMENTS OF DYNAMIC STABILITY DERIVATIVES IN THE T-38 WIND TUNNEL

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Abstract

Low amplitude of signals in measurements of stability derivatives is a known problem. Solution by applying semiconductor strain gauges is presented. Foil strain gauge balance was replaced with a semiconductor five-component strain gauge balance, and semiconductor excitation moment sensor was applied. Wind tunnel test data are presented.

1 Introduction

In the first dynamic stability tests performed in the T-38 wind tunnel [1], the problem of small amplitudes of output signals from forces and moments sensors, common in measurements of dynamic stability derivatives, was encountered. A solution of this problem by application of semiconductor strain gauges is presented in this paper, with emphasis on the effects on measurements of dynamic stability derivatives in roll.

Semiconductor strain gauges provide high level of output signals even at low levels of strain, which makes them very useful in measuring small loads with accuracy and precision. Introduction of these gauges in measurements of stability derivatives in the T-38 wind tunnel required some modifications on the already built apparatuses. One modification was the replacement of the foil strain gauge force balance with a semiconductor five-component strain gauge balance. Usage of semiconductors strain gauges insured increased balance sensitivity as well as increased stiffness of the balance in all degrees of freedom. The second modification is made on the roll apparatus. The excitation moment sensor made with foil strain gage was substituted by one made with semiconductor gauges.

These modifications were followed by series of wind tunnel measurements of stability derivatives. One of them was roll-damping measurement of the Modified Basic Finner Model, MBFM, a standard calibration model for measurements of stability derivatives.

2 Description of Measurement Equipment and Technique

The T-38 test facility of VTI is a blowdown-type pressurized wind tunnel with a 1.5m x 1.5m square test section, Figure 1 [2]. For subsonic and supersonic tests, the test section is with solid walls, while for transonic tests, a section with porous walls is inserted in the tunnel configuration. Mach number in the range 0.2 to 4.0 can be achieved in the test section, with Reynolds numbers up to 110 million per meter. Run time is in the range 6s to 60s, depending on Mach number and stagnation pressure. Model is supported in the test section by a tail sting mounted on a pitch-and-roll mechanism by which desired aerodynamic angles can be achieved. The facility supports both step-by-step model movement and continuous movement of model (“sweep”) during measurements.

The technique for measurements of stability derivatives applied in the T-38 wind tunnel is forced oscillation technique.

According to this technique model is forced to oscillate at constant amplitude within a single degree of freedom, which implies that any aerodynamic reaction coherent with such motion, donated as “the primary motion”, can only be due to such motion.

Fig. 1. T-38 wind tunnel

All the experiments are based on application of small/amplitude oscillatory motion to a model in the primary degree of freedom and measurement of aerodynamic reactions produced by such motion in that particular and in other (secondary) degrees of freedom. Those reactions, in turn, yield relevant direct and cross as well as cross-coupling derivatives due the motion considered herein. A typical wind-tunnel run includes the following stages:

- Tare run, when the model is oscillated but the tunnel is not running. This measurement enables determination of the inertial forces.
- Wind-on run, when the model is oscillated at the frequency same as during the tare run but with the wind tunnel running.

Dynamic stability derivatives are obtaining by subtracting data from tare run and wind-on run. For a primary degree of freedom for model oscillatory motion in rolling plane, determination of direct static and damping stability derivatives is expressed in equation (1). In equation (1) all values with index ‘0’ are measured in tare run [3-5].

$$L_\beta \sin\alpha = I\left(\omega_0^2 - \omega^2\right) + \left(\frac{|L|\cos\eta}{|\varphi|}\right)_0 - \left(\frac{|L|\cos\eta}{|\varphi|}\right) \quad (1)$$

$$L_p + L_{\dot\beta} \sin\alpha = \left(\frac{|L|\sin\eta}{|\varphi|\omega}\right)_0 - \left(\frac{|L|\sin\eta}{|\varphi|\omega}\right)$$

In equation (1) are: $L_\beta \sin\alpha$ [Nm/rad]- rolling moment derivative due to sideslip, $L_p + L_{\dot\beta} \sin\alpha$ [Nms/rad] – direct damping derivative in roll, I [kgm^2]– moment of inertia, ω [rad/s]–angular velocity, $|L|$ [Nm] – amplitude of excitation moment, $|\varphi|$ [rad] – amplitude of primary motion, η [°] – phase shift .

For determination of direct stability derivatives following physical values must be measured:

- amplitudes of primary motion and excitation moment,
- frequency of primary motion,
- phase shift between excitation moment and primary motion.

Two apparatus for measurements of stability derivatives were designed and produced in VTI. The first one is for measurements of stability derivatives in rolling, and the second one is for measurements of stability derivatives in the pitching and yawing.

CAD model and photograph of the Roll apparatus are shown on Figures 2. and 3. Primary motion is impaired by hydraulic driving mechanism located at the rear end of the sting. Flexure support consists of two rings jointed by axially oriented beams equal spaced around the periphery of the rings. A five component balance is mounted on the front and of the drive shaft, protruding forward trough the cavity surrounded by the suspension beams, while the aft part of suspension system is firmly fixed to the end of the sting.

Roll apparatus includes following sensors: primary oscillatory motion sensor, excitation moment sensor and feedback position sensor. On the flexure support are mounted two roll position sensor realized as foil strain gauges. Excitation moment is measured via a strain gauge on the front end of the drive shaft.

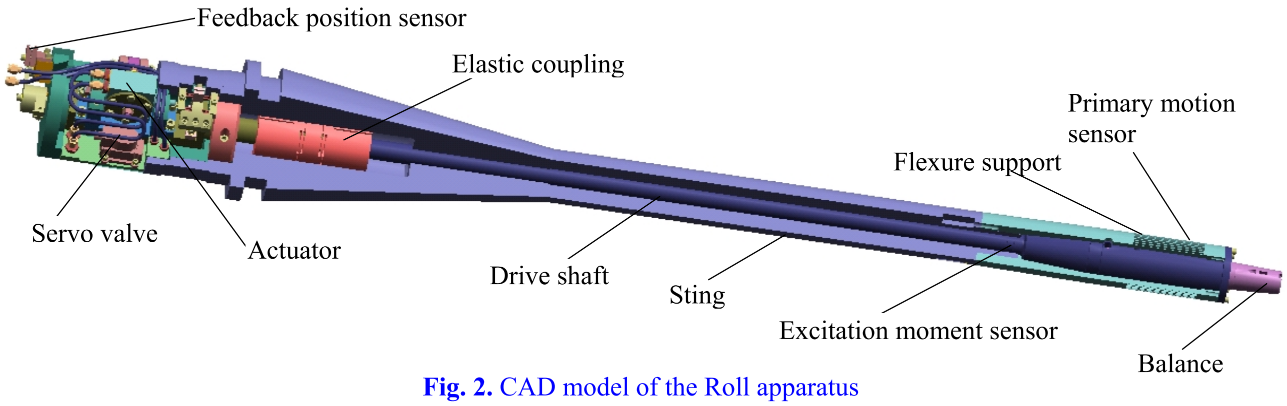

Fig. 2. CAD model of the Roll apparatus

Fig. 3. Roll apparatus

Performances of Roll apparatus are:

- amplitude 0.25°÷1.5°
- sting diameter 76 mm
- maximum axial force 5.5 kN
- maximum normal force 10 kN
- maximum pitching moment 660 Nm
- frequency 1÷25 Hz
- hydraulic pressure 200 bar
- maximum side force 7 kN
- maximum rolling moment 300 Nm
- maximum yawing moment 350 Nm.

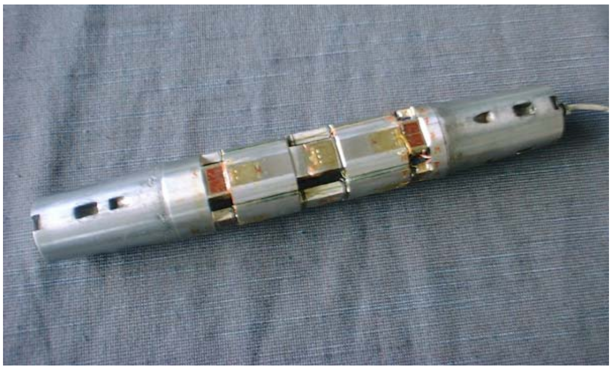

Fig. 4. Force balance with semiconductor strain gauges

3 Description of the Modifications of the Roll Apparatus

3.1 Semiconductor Five-Component Strain Gauge Balance

In order to improve stability derivatives measurements, the first modification was the replacement of the foil strain gauge force balance with a semiconductor five-component strain gauge balance, Figure 4.

Balance is manufactured out of one piece, by shaping particular section to obtain “single component” transducers. Strain gauge balance material is high-quality ARMCO PH13.8-Mo steel, with high mechanical performances, good machinability, and high corrosion resistance. The measurement of the normal force and the pitching moment, as well as the side force and yawing moment is obtained through the forward and backward measuring section shaped as a three bar cage. The measurement of the rolling moment is obtained through the central measuring section shaped as a five bare cage.

The semiconductor strain gauges are conected in form of four-arm bridges, Figure 5. [6].

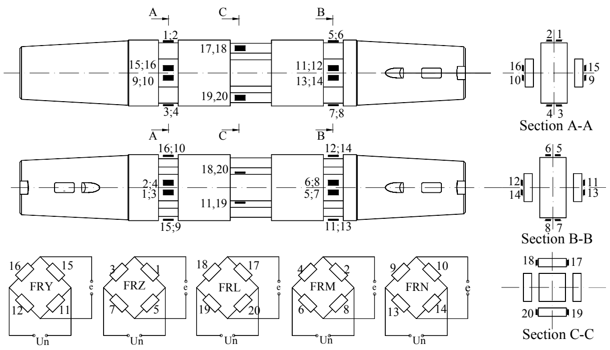

Fig. 5. Position of the measuring section and the measuring bridges

The design load of the force balance and maximum value of output signals of the balance component are shown in the table 1.

Balance was calibrated using an advanced technique [7] that permits simultaneous application of loads on more than one measuring component of the balance, Figure 6.

Table 1. Balance component and design load

Component	Design load	Maximum value of output signals
FRY-side force	7060 N	483 mV
FRZ- normal force	10150 N	546 mV
FRL-rolling moment	300 Nm	412 mV
FRM- pitching moment	660 Nm	695 mV
FRN-yawing moment	340 Nm	499 mV

Fig. 6. Strain gauge-balance on the VTI six-component calibration ring

The idea behind this approach is that the loading configuration during calibration should be representative of the conditions in which the balance will be during a wind tunnel test. During calibration, each component is loaded at least 5 increments from zero to maximum load. Coefficients of the calibration matrix were calculated for each component by least-squares method using data from a complete representative load subset. Table 2. lists a summary of achieved accuracy of the calibration, as obtained in a checkout after the calculation of the calibration matrix. Checkout was performed on the same load subset that was used to calculate the matrix.

Accuracy achieved in balance checkout is displayed on the graphs in Figure 7. Nominal component accuracies (displayed with lines on the graphs) are 0.2%.

Table 2. Summary of achieved accuracy

Component	Maximum errors [% FS]	Standard deviation of errors [%FS]
FRY	-0.102	0.034
FRZ	0.162	0.040
FRL	-0.156	0.054
FRM	0.076	0.028
FRN	0.144	0.048

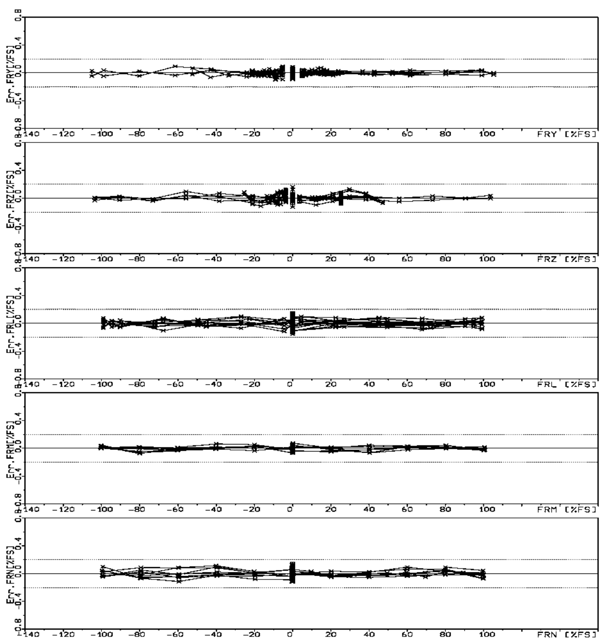

Fig. 7. Accuracy achieved in balance checkout in all cases during calibration

3.2 Semiconductor Excitation Moment Sensor on the Drive Shaft

The second modification was the replacement of the excitation moment sensor on the drive shaft. The earlier sensor with foil-type strain gauges was substituted by one made with semiconductor strain gauges. The gages axis is inclined at 45° to the longitudinal axis of drive shaft. The semiconductors strain gauges are connected in form of four-arm bridges.

Calibration of excitation moment sensor was performed in wind tunnel test section, Figure 8. Result of this calibration is shown on the Figure 9.

Fig. 8. Calibration of the excitation moment sensor

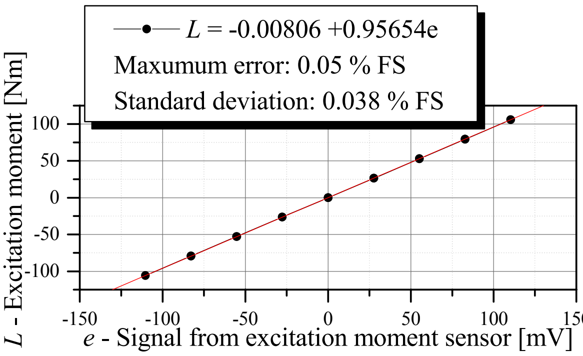

Fig. 9. Result of the excitation moment sensor calibration

Amplitudes of the excitation moment, $|L|$ in equation (1), are determinate from the amplitudes of the excitation moment signals. Amplitudes of the excitation moment signals measured by semiconductor and foil strain gauges, for the same model (Modified Basic Finner Model) and at the same tests conditions, are compared in the graph in Figure 10. Average value of signal amplitude from semiconductor excitation moment sensor is 11.9 mV, whereas average value of signal amplitude from foil excitation moment sensor is 0.185 mV. It is obvious that semiconductor sensor provides much higher signal levels. Using semiconductor strain gauges a large signal to noise ratio is achieved, which is very important for calculating phase shift between signals of excitation moment and primary motion of the model.

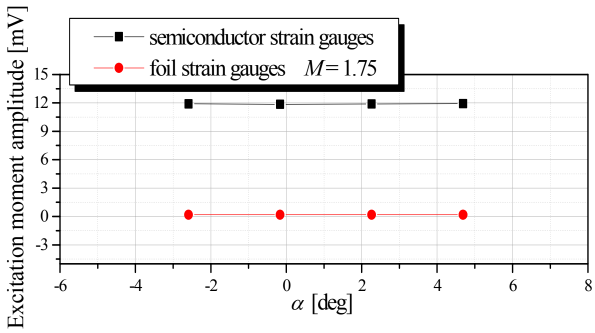

Fig. 10. Amplitude of the excitation moment sensors

4. Tests Results of Roll-Damping Measurements

Roll-damping measurements of the Modified Basic Finner Model (MBFM) made using the modified instrumentation with semiconductor strain gauges were performed at Mach numbers: 0.6, 1.15 and 1.75. The complex angles of attack were in the interval from -5° to +5° and roll angle was 0°.

Modified Basic Finner Model geometry is a 2.5 caliber tangent-ogive cylinder fuselage with trapezoidal fins in the + configuration. The center of mass is located 5 diameters from the nose along the longitudinal axis of the body. Basic dimensions of the MBFM model are presented on the Figure 11.

MBFM model mounted in the T-38 test section is shown on the Figure 12. Tests results are presented in form of graphs on figures 13 to 15.

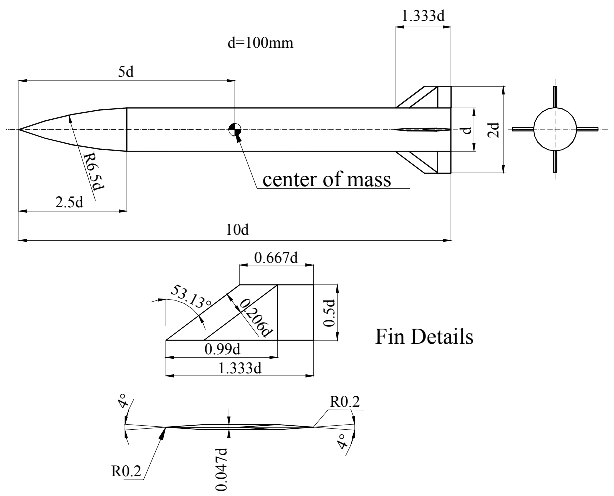

Fig. 11. Basic dimension of the MBFM model

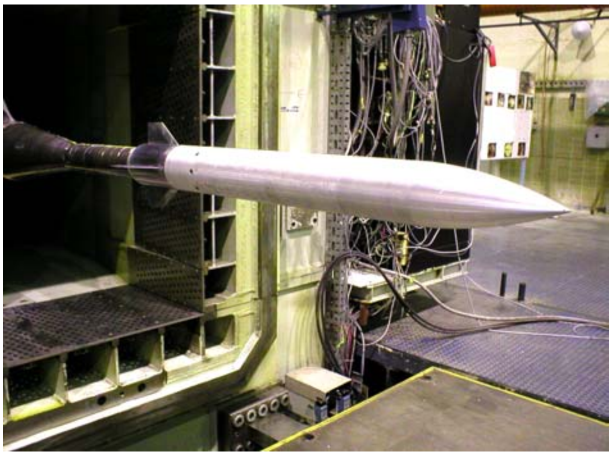

Fig. 12. MBFM model in the T-38 test section

Tests results for the MBFM model obtained in the T-38 wind tunnel are compared with published experimental data from the AEDC wind tunnel [8](Arnold Engineering Development Center-von Karman - USA).

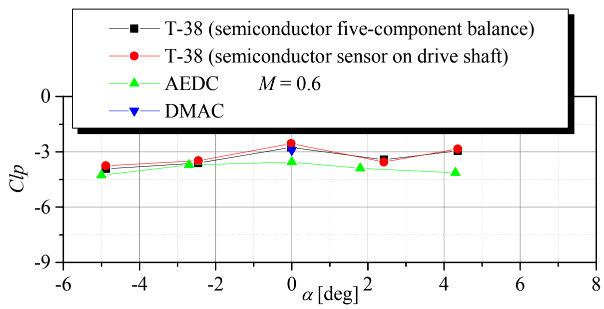

Fig. 13. Roll – damping derivative for the MBFM model at the $M = 0.6$

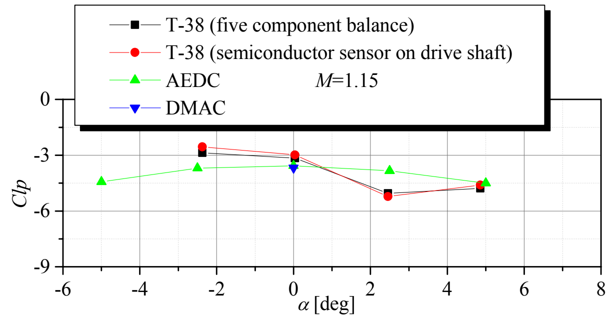

Fig. 14. Roll – damping derivative for the MBFM model at the $M = 1.15$

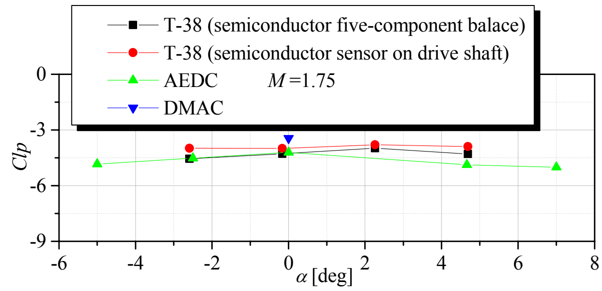

Fig. 15. Roll – damping derivative for the MBFM model at the $M = 1.75$

Wind tunnel data for all Mach numbers at $\alpha = 0°$ are also compared with calculated roll-damping coefficient values obtained by DMAC semi-empirical method developed in the VTI [9].

Amplitudes of the excitation moment, $|L|$ in equation (1) can be determined from balance bridge for rolling moment or from semiconductor sensor on drive shaft. Comparisons of roll-damping derivatives determined by excitation moments from these two sensors show good agreement at all Mach number (Figure 13. -15.). The amplitude and phase shift of the excitation moment are calculated in frequency domain by applying the cross-power spectral density. Signals from excitation moment sensors are cross-correlated with the primary signal generated by primary oscillation motion sensor.

The duration of a typical dynamic test in the T-38 wind tunnel is approximately 10 seconds. In presented experiments one test run was done for each angle of attack. The duration of test runs was 12 seconds, where approximately 8 seconds was sampling time. Finally, cross-correlation functions were determinate from 82 periods of model oscillations.

Measurement of dynamic stability derivatives is very delicate process. Agreement between the test data from the T-38 wind tunnel and published experimental data is very good.

5. Conclusions

Use of semiconductor strain gauges in measurements of dynamic stability derivatives is described in this paper. Introduction of these gauges required some modifications on apparatuses for stability derivatives measurements. Two modifications on the roll apparatus were done: foil strain gauge force balance was substituted with semiconductor strain gauge balance and foil-type excitation moment sensor was substituted with semiconductor excitation moment sensor.

It is shown that problem of small amplitudes of output signals from forces and moments sensors can be solved using semiconductors strain gauges. Semiconductor strain gauges provides much higher signal levels and large signal to noise ratio which is very important for calculating necessary values for determination stability derivatives with described technique.

Roll-damping measurements of the Modified Basic Finner Model, conducted with modified roll apparatus showed very good results. It has been concluded that application of instrumentation based on semiconductor strain gauges has improved the quality of wind tunnel measurements of dynamic stability derivatives and that obtained results agree well both with published experimental data and with semi-empirical data.

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