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Looking for the last dragcount - model vibrations vs. drag accuracy

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ABSTRACT
The paper inverstigates the influence which vibrations of a windtunnel model have on the reading of the axial force as measured by an internal strain-gage balance. When the model vibration modes exhibit a finite bending radius - as they usually do - centrifugal accelerations are generated. These will act on the model mass and thus cause a bias on the axial force or drag reading of the balance. Though this effect is not spectacular, it is certainly not always negligible: errors can be up to five dragcounts.
The paper is an extension of an earlier study on the compensation of comparable effects in gravity sensing angle-of-attack inclinometers. It presents a theoretical analysis and some typical quantitative results. Based on this analysis a simple but effective compensation scheme is proposed: it uses only four signals from the inclinometer signal conditioning and some model dat such as mass and center of gravity location.

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SUMMARY

The paper investigates the influence which vibrations of a windtunnel model have on the reading of the axial force as measured by an internal strain-gage balance. When the model vibration modes exhibit a finite bending radius - as they usually do - centrifugal accelerations are generated. These will act on the model mass and thus cause a bias on the axial force or drag reading of the balance. Though this effect is not spectacular, it is certainly not always negligible: errors can be up to five dragcounts.
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SYMBOLS

AOA	Angle of attack
c.g.	Center of gravity
C_D	Drag Coefficient
ε	Centrifugal Acceleration
F_ε	Bias on Axial Force of SGB
kg	kilogram mass
ℓ	Model length
m	meter
M	Model mass
N	Newton
ν	Frequency
Q	Dynamic Pressure
r	Distance between Accelerometers
R	Bending radius
$\dot{\rho}$	Angular rate
s	second
S	Reference Surface of Model
SGB	Strain Gage Balance
$\dot{\tau}$	Tangential Speed
x	Distance from inclinometer
z	Vibration amplitude

INTRODUCTION

It is generally recognized that model vibrations involving a finite bending radius can severely affect the accuracy of gravity-vector sensing inclinometers in windtunnel models. Due to ’sting whip’ and other related motions - e.g. around the balance center - centrifugal accelerations are generated which can easily cause errors of up to .5 deg in angle-of-attack (AOA). Although equally obvious, it is much less appreciated that (part of) these centrifugal accelerations will also act on the model mass and will therefore cause a deviation in the axial force reading of an internal strain-gage balance (SGB). The errors created by this effect may not be spectacular - they are certainly not always negligible as illustrated by the example below.

For a typical model on a Z-sting in the NLR HST Transonic Windtunnel the following figures apply:

Model mass	:	$M = 50$	kg
Pitch frequency	:	$\nu = 16$	Hz
Bending radius	:	$R = 1.1$	m
Vibration Amplitude	:	$z = 2$	mm

The peak centrifugal acceleration under these conditions is .036 m/s^2, the relevant average value is half of that or .018 m/s^2. With the model mass of 50 kg this acceleration causes an axial force of .9 N. The aerodynamic parameters for this model would be:

Dynamic pressure	$Q = 30000\ N/m^2$
Reference surface	$S = 0.15\ m^2$

This means that one ’dragcount’ or .0001 in C_D is equivalent to .45 N and that the bias in this case is two dragcounts! It should be reminded that this figure applies for a single mode and that many more modes (in pitch and yaw) can contribute. In an era where a reproducibility of .5 dragcounts in C_D is desired this error source obviously cannot always be neglected.

Another approach to illustrate the point is to look at the bias on the inclinometer readings. For the values given above the error in AOA would be .1 deg, which is not unusual. In practice AOA errors up to .5 deg are encountered, but fortunately mostly under buffet conditions, where the requirements on drag-accuracy are relaxed. The errors on AOA and the compensation of these have been discussed extensively in reference 1, from which figure 1 is taken. It gives the bias on AOA during a polar and thereby implicitly the order if magnitude of potential errors (depending on the mode) on drag. For this model .1 deg $\Delta\alpha$ in AOA could be equivalent to 2 dragcounts, the error in drag being proportional to the error in AOA for this mode.

The nature of the bias is such that it will apparently reduce the drag - the centrifugal acceleration vector points outward. Its amplitude will have a stochastic character, causing a small constant bias plus some scatter on axial force. The point should be stressed that the bias increases quadratically with model vibration amplitude - another reason to keep model vibration levels low!

The conclusion of the above is that a correction on axial force is desirable and worthwhile, but since it is relatively small the absolute accuracy of the correction can be limited to some 10 %.

ANALYSIS

Any quantitative correction scheme must be based on a kinematic analysis of the actual model vibrations involving all simultaneous vibration modes. The basis for this is provided by reference 1, which does exactly that for the influence of model vibrations on inclinometers for AOA measurement. The compensation proposed therein has been fully validated in actual windtunnel use.
At first sight the calculation of the influence on drag might look simple: multiply the bias on the inclinometer by the model mass, et voilà. Unfortunately real life is more complicated than that: not all vibration modes produce a net contribution to the axial force bias. A vibration around the c.g. of the model for instance might create opposite forces fore and aft of the c.g. and have near zero net effect. An inclinometer (not mounted in the c.g.) however would be affected.

In reference 1 it was proven that for any arbitrary point on the model (including the location of the inclinometer) the centrifugal acceleration ε is given by the product of the local tangential speed $\dot{\tau}$ and the angular rate $\dot{\rho}$ (Fig. 2), or:

$$\varepsilon = \dot{\tau} \cdot \dot{\rho} \qquad (1)$$

This expression is valid for any combination of simultaneous vibration modes. It must be applied twice: in the x-z plane and in the x-y plane of the model.

The total net axial force bias F_ε is obtained by multiplying the local ε_x by the local mass M_x for that particular 'slice' of the model and integrating the product over the length of the model, or:

$$F_\varepsilon = \int_o^{\ell} \varepsilon_x \cdot M_x \, dx \qquad (2)$$

This expression looks simple, but is not very convenient to work with - even more so because ε_x relates to momentary local values.

COMPENSATION

The compensation of course is equal to F_ε as given by equation (2). The big challenge is to find a user-friendly expression for ε_x - in order to avoid an array of accelerometers over the length of the model! The constituents of ε are $\dot{\tau}$ and $\dot{\rho}$, as given by equation (1). The angular rate $\dot{\rho}$ is constant over the length of the model. It can either be measured directly or be derived from two linear accelerometers as sketched in figure 3:

$$\dot{\rho} = \frac{\dot{\tau}_1 - \dot{\tau}_2}{r} \tag{3}$$

It should be reminded that it is not possible to measure or assess the momentary bending radius R directly, but it can be deduced from measurable quantities as:

$$R = \frac{\dot{\tau}_1}{\dot{\rho}} \tag{4}$$

Assuming $\dot{\tau}_1$ and $\dot{\rho}$ are known because they are required for the inclinometer compensation, $\dot{\tau}_x$ at an arbitrary distance x from $\dot{\tau}_1$, (Fig. 3) is given by:

$$\dot{\tau}_x = \dot{\tau}_1 + \dot{\rho} \cdot x \tag{5}$$

Note: x can be positive or negative.

The local centrifugal acceleration ε_x at a distance x from the reference location of $\dot{\tau}_1$ then becomes:

$$\varepsilon_x = \dot{\rho} \cdot \dot{\tau}_x = \dot{\rho} \cdot \dot{\tau}_1 + \dot{\rho}^2 \cdot x \tag{6}$$

The first right-hand term is the original inclinometer compensation from reference 1 and is independent of x. Thus, for axial force bias compensation purposes, it can be directly multiplied by the total model mass M. The second term can be regarded as a correction on the first one. Depending on the direction of x its contribution can be positive or negative.

Combining equation (2) and equation (6) the complete expression for the axial force bias thus becomes:

$$F_\varepsilon = M \cdot \dot{\rho} \cdot \dot{\tau}_1 + \dot{\rho}^2 \int_0^{\ell} M_x \cdot x \cdot dx \tag{7}$$

in which ℓ is the length of the model.

The integral term represents a moment with respect to the position where $\dot{\tau}_1$ is measured, i.e. the inclinometer location. The mass is the model mass M and the arm is the distance x_{cg} between the center of gravity of the model and the inclinometer location. Expression (7) can thus be simplified to:

$$F_\varepsilon = M \left(\dot{\rho} \cdot \dot{\tau}_1 + \dot{\rho}^2 \cdot x_{cg} \right) \tag{8}$$

This result is in-line with what one would intuitively expect. It is relatively simple and all quantities can be measured or assessed. Normally the c.g. of the model will be located aft of the inclinometer, so x_{cg} will be negative. It should be emphasized that all of the above reasoning is based on the assumption that the models, including their built-in instrumentation, are sufficiently stiff: i.e. have no resonances in the vicinity of the compensated modes.

IMPLEMENTATION

The correction for bias on axial force as proposed in this paper is - not surprisingly - closely related to the compensation of the AOA inclinometer for the same centrifugal acceleration effects. For the latter application a dedicated and validated 'Inclinometer Conditioning Unit' is available at NLR. It provides a fully corrected AOA output with a resolution of .001 deg. The compensations functions are

realized with analog techniques, as shown on the block diagram of figure 4.
For each plane of the axial force bias compensation two extra output signals are required: $\dot{\rho} \cdot \dot{\tau}_1$ and $\dot{\rho}^2$. They are made available, as indicated in figure 4, for digitization by the regular data acquisition system. The model mass - including the weighed part of the balance - can be weighed directly or can be obtained from the usual wind-off 'weight polar' in the windtunnel. The same applies to the distance x_{cg}. With all variables known the processing (in two planes!) according to equation (8) is elementary.

CONCLUSION

The paper presents a compensation for the small, but not negligible, bias effect on drag of windtunnel models due to model vibrations. The proposed scheme is simple, transparent and accurate and can be applied in real time.
Admittedly it is based on a theoretical analysis and has not yet been validated during real windtunnel testing. A comparable compensation for AOA Inclinometers however has been proven in practice and has shown to be extremely accurate, leaving no doubt as to the applicability of the scheme proposed here.

REFERENCE

1. Fuijkschot, P.H., National Aerospace Laboratory NLR, *Vibration Compensation of Gravity Sensing Inclinometers in Windtunnel Models*, Proceedings ISA 42nd International Instrumentation Symposium, pp. 493-503, May 1996, San Diego, NLR Report TP 96003 L.