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VIBRATION COMPENSATION OF GRAVITY SENSING INCLINOMETERS IN WINDTUNNEL MODELS

by

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ABSTRACT
This paper describes a remarkably simple technique for compensating the output of gravity sensing inclinometers for bias errors due to centrifugal accelerations. These inclinometers are commonly used in windtunnel models for measuring angle of attack (AOA). The required accuracy is .01 deg, which is no problem under static conditions. However, during wind-on aerodynamic excitation of the vibration modes of the model-balance-sting-support combination cause errors due to centrifugal accelerations which can exceed the required accuracy by one or two orders of magnitude. It is shown in the paper that by including a few extra accelerators in the model, combined with appropriate signal processing, it is possible to compute an accurate compensation in real-time, irrespective of the number of simultaneous modes.
The paper includes a theoretical analysis, some results of experimental verification during actual windtunnel testing and a discussion in implementation.

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Vibration Compensation of Gravity Sensing Inclinometers in Windtunnel Models

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KEYWORDS

Angle of Attack, Angle of Incidence, Inclinometers.

ABSTRACT

The paper describes a remarkably simple technique for compensating the output of gravity sensing inclinometers for bias errors due to centrifugal accelerations. These inclinometers are commonly used in windtunnel models for measuring angle of attack (AOA). The required accuracy is .01 deg, which is no problem under static conditions. However, during wind-on aerodynamic excitation of the vibration modes of the model-balance-sting-support combination cause errors due to centrifugal accelerations which can exceed the required accuracy by one or two orders of magnitude. It is shown in the paper that by including a few extra accelerometers in the model, combined with appropriate signal processing, it is possible to compute an accurate compensation in real-time, irrespective of the number of simultaneous modes.

The paper includes a theoretical analysis, some results of experimental verification during actual windtunnel testing and a discussion on implementation.

SYMBOLS

A	Inclinometer output	g	gravitational constant
α	Angle of Attack/Incidence	ε	centrifugal acceleration error
β	Yaw Angle	τ	translation
γ	Roll Angle	ρ	rotation
AOA	Angle of Attack	ω	circular frequency
C_A	Axial Force coefficient	N	Newton
C_D	Drag coefficient	m	meter
C_N	Normal Force coefficient	s	second
C_L	Lift Coefficient	kg	kilogram
V	Speed	δ	angular amplitude
R	Bending radius	r	distance

INTRODUCTION

The majority of windtunnels nowadays feature sting supported models using an internal six-component strain gage balance (SGB) for measuring aerodynamic forces and moments. Typical for this configuration is that the aerodynamic loads are resolved in the model axis system. Since the aerodynamicists are primarily interested in the forces and moments acting on the model in the flow axis system axis transformations are required. The most critical one of these is performed in the x-z plane and involves a rotation over the angle of attack (AOA) α of the model. Expressed in terms of coefficients the four relevant vectors are: normal force C_N, lift C_L, axial force C_A and drag C_D. Disregarding small corrections the relations between these are (Fig. 1):

$$C_D = C_A \cdot \cos\alpha + C_N \cdot \sin\alpha, \qquad C_L = C_N \cdot \cos\alpha - C_A \cdot \sin\alpha \tag{1}$$

or, simplified, since α is small in the range of cruise conditions of interest here:

$$C_D = C_A + C_N \cdot \alpha, \qquad C_L = C_N - C_A \cdot \alpha \tag{2}$$

Since C_N is much larger than C_A (Typically .6 vs .03), the angle α has to be established with great precision to assure the required accuracy of one 'dragcount' or .0001 in C_D. The maximum error in α thus is 1 in 6000 (of a radian!) or .01 degree.

The angle α is defined with respect to the flow vector, for obvious practical reasons it is either measured with respect to the test section walls, the model support, or the gravity vector. Each of these methods has its own specific drawbacks.

Using the test section walls as a reference usually implies optical techniques (OPTOTRAK, ELOPTOPOS, Boeing, Complere, ETW-Bertin), which means they are subject to changes in refractive index in the test section flow (shockwaves!). Errors of this nature are not negligible, difficult to predict and difficult to correct for. Moreover the test section walls themselves sometimes are adjustable, doubling the accuracy problem.

It is possible to measure the angle directly on the model support, but the less than perfect deformation corrections combined with play and hysteresis in the mechanical joints limit the attainable accuracy to some .1 degree. Nevertheless it is an indispensable measurement, if only for monitoring and control.

Provided tunnel and test section are founded and constructed sufficiently stable, the direction of the local gravity vector can be used as a reference for assessing AOA. A high precision (servo-) accelerometer is mounted with its sensitive axis parallel to the model axis. This way its output is nominally zero at zero incidence and at an angle α the accelerometer output A equals g $\sin\alpha$. Provided the local gravitational constant g and the accelerometer calibration are known, the angle α can simply be resolved. Under static conditions a resolution of .001 and an accuracy of .002 degree can easily be realized.

However, under wind-on conditions sting-mounted models tend to vibrate in a variety of modes determined by the particular model-balance-sting-support combination. When these vibrations have a rotational component - and they usually do- centrifugal accelerations are generated which will directly affect the inclinometer output and thus introduce errors. Because of their quadratic nature (V^2/R), their mean value is non-zero and consequently they cannot be removed by averaging or low-pass filtering.

These errors have been known and identified ever since people started using servo-accelerometers as inclinometers in windtunnel models, i.e. since the early seventies. Of course efforts have been made to devise schemes for compensation (Ref. 1, Ref. 2), but up to now only with marginal success under operational conditions.

Obviously there is no ideal AOA system yet, even though over the past two or three decades millions of dollars have been spent on development and implementation of (mostly) optical systems. In many cases the phase of operational maturity was never reached. On the contrary the compensation scheme for gravity sensing inclinometers proposed in this paper is relatively simple and inexpensive, does not require exotic instrumentation, and is small, accurate and reliable.

EVALUATION

The typical model/inclinometer/balance/sting configuration is sketched in Fig. 2. It is clear that the inclinometer is subject to an acceleration A given by:

$$A = g\sin\alpha \quad \text{or:} \quad \alpha = \arcsin\frac{A}{g} \tag{3}$$

Under wind-off or quasi-static conditions this is perfectly true and α can easily be resolved to an accuracy of .002 degree. During wind-on the model will be subject to aerodynamically induced vibrations in a variety of modes, some of which can severely affect the accuracy of AOA measurement.

In general pure translations will have no effect on AOA. For instance, sometimes large vibrations may be present in the direction of the model x-axis, but these can be averaged out by low-pass filtering. Nevertheless care should be taken because their amplitude can be one or two orders of magnitude larger than the mean acceleration due to incidence. At 6 degrees AOA e.g. the latter is only .1 g or .6 % of the full range of a Q-Flex.Extreme linearity of sensor and signal conditioning and a wide dynamic range are essential.

The real problem area is where the vibrations have a rotational component. A typical situation for a single mode in the x-z plane of the model is sketched in Fig. 3. With an apparent bending radius R a tangential velocity $\dot{\tau}$ will cause a centrifugal acceleration or error ε given by:

$$\varepsilon = \frac{\dot{\tau}^2}{R} \tag{4}$$

In the case of Fig. 3 the error vector ε points outward, thus biasing A according to:

$$A' = g\sin\alpha - \frac{\dot{\tau}^2}{R} \quad \text{so:} \quad \alpha' = \arcsin\left(\sin\alpha - \frac{\dot{\tau}^2}{gR}\right) \tag{5}$$

For α around zero and small errors the deviation from the nominal AOA expressed in radians is given by:

$$\alpha_\varepsilon = -\frac{\dot{\tau}^2}{gR} \tag{6}$$

This is a momentary value, for a harmonic movement with $\dot{\tau}$ as amplitude the filtered or mean value is half of that. The quadratic relation between ε or α_ε and $\dot{\tau}$ for a single mode is sketched in Fig. 4, the dashed line symbolizes the mean value.

The severity of the problem is illustrated by the following example, which uses typical values including a not spectacular vibration amplitude of 3 mm. For a (pitch) frequency of 15 Hz and an apparent bending radius of 1 m the average error in AOA would be -.23 deg, which is 20 to 50 times the required accuracy! According to NLR experience transonic models under cruise conditions may show AOA errors up to .05 or .1 deg, while during buffet or stall .5 deg may occur.

Complicating the problem is the experience that in practice there are many simultaneous modes, acting in different planes and all with different frequencies, bending radii and amplitudes. Moreover these quantities are influenced by aerodynamic loading and are stochastic in nature. The unknown and hard to assess bending radii make it difficult to predict which mode will be the predominant one contributing to the error. A spectacular looking low frequency yaw motion with a long bending radius may be far outweighed by an almost invisible movement around the balance center at a five times higher frequency. Earlier attempts at NLR for a dual (Z and Y) single mode compensation (Ref. 2) produced unreliable results because of this.

The conclusion of the above is that any potentially successful compensation method should be based on the actual momentary motions of the model and thus cope with any number of simultaneous modes with modulated amplitudes. It also means that there should be no time domain data skew between the inclinometer output and the compensation signals. The compensation scheme discussed in this paper meets these conditions.

An example of the typical pattern of the deviations caused by centrifugal effects is given In Fig. 5. As one would expect, all errors are in the same direction, i.e. an apparently more negative AOA. In the normal cruise region below 4 deg there are incidental peaks up to .07 deg, at buffet onset near 4.5 deg the error rapidly increases to .6 deg in this case. The system described in Ref. 3 was used as reference for the true AOA.

It should be mentioned that the centrifugal effects may also directly and appreciably affect the reading of the drag component of an internal six-component balance. It would therefore be practical to assess not only the correct angle but also the centrifugal acceleration as a separate signal. Using the known model weight a correction on drag can then be calculated. For the numerical example given above the centrifugal acceleration would be .08 m/s^2, which would, assuming a model mass of 60 kg, cause a bias in drag of 5 N. This could represent two to three dragcounts for this size of model.

COMPENSATION

The basic reasoning behind the proposed compensation is that once the relevant model movements are known, it should be possible to compute the momentary centrifugal acceleration and thus the appropriate correction. The original analysis, based on theoretical considerations only, was given in Ref. 4.

According to Euclidian kinematics the motion of any solid body can be described by the translations along three axes and the rotations around these three axes. Normally this would relate to an axis system fixed in space, but for the purpose envisaged here -essentially dealing with rotations only- it is easier to refer to a body (model) related axis system.

For a single mode in the model X-Z plane the following relations apply for a harmonic rotation around the Y-axis:

$$\begin{aligned} &\text{Angle} && \rho = \delta \cdot \sin \omega t \\ &\text{Rate} && \dot{\rho} = \delta \cdot \omega \cdot \cos \omega t \\ &\text{Acceleration} && \ddot{\rho} = -\delta \cdot \omega^2 \cdot \sin \omega t \end{aligned} \qquad (7)$$

The momentary angle is given as ρ, the amplitude as δ and the circular frequency as ω.

If that particular mode has an apparent bending radius R (Fig. 3) the corresponding tangential movements τ are obtained by multiplying the above angular quantities by R:

$$\begin{aligned} &\text{Position} && \tau = R \cdot \delta \cdot \sin \omega t = R \cdot \rho \\ &\text{Speed} && \dot{\tau} = R \cdot \delta \cdot \omega \cdot \cos \omega t = R \cdot \dot{\rho} \\ &\text{Acceleration} && \ddot{\tau} = -R \cdot \delta \cdot \omega^2 \cdot \sin \omega t = R \cdot \ddot{\rho} \end{aligned} \qquad (8)$$

The inclinometer is assumed to be located at the end of the bending radius vector R. Applying the elementary expression for the centrifugal acceleration then produces:

$$\varepsilon = \frac{\dot{\tau}^2}{R} = \frac{R^2}{R} \cdot \delta^2 \cdot \omega^2 \cdot \cos^2 \omega t \quad \text{or :} \quad \varepsilon = R \cdot \dot{\rho}^2 = \frac{R \cdot \delta^2 \cdot \omega^2}{2} (1 + \cos 2 \omega t) \qquad (9)$$

The '1' between brackets represents the bias error, because cos $2\omega t$ can be filtered out. The $\dot{\tau}$ or $\dot{\rho}$ terms can be measured, but the apparent bending radius R is very difficult to assess in practice, especially since there will be more than one vibration mode simultaneously.

If, however, the two expressions for ε are multiplied we get:

$$\varepsilon^2 = \frac{\dot{\tau}^2}{R} \cdot R \cdot \dot{\rho}^2 = \dot{\tau}^2 \cdot \dot{\rho}^2 \quad \text{or :} \quad \varepsilon = \dot{\tau} \cdot \dot{\rho} \qquad (10)$$

The last expression is independent of R and uses only quantities which are relatively easy to establish: translational and rotational speed. So, the correction term for centrifugal effects is given by the momentary tangential speed times the angular rate of the inclinometer. This process must be applied twice: in the X-Z plane of the model and in the X-Y plane, the results of which must be added.

The above reasoning applies for a single bending radius R. It still has to be proved that the principle is also applicable if more than one vibration mode is present. To this end assume two simultaneous modes with respectively R_1 and R_2, ω_1 and ω_2, δ_1 and δ_2. Then, with linear superposition:

$$\begin{aligned} \dot{\rho} &= \delta_1 \cdot \omega_1 \cdot \cos \omega_1 t + \delta_2 \cdot \omega_2 \cdot \cos \omega_2 t \\ \dot{\tau} &= R_1 \cdot \delta_1 \cdot \omega_1 \cdot \cos \omega_1 t + R_2 \cdot \delta_2 \cdot \omega_2 \cdot \cos \omega_2 t \end{aligned} \qquad (11)$$

The product term, which should produce the compensation, then becomes:

$$\begin{aligned} \dot{\rho} \cdot \dot{\tau} = {} & R_1 \cdot \delta_1^2 \cdot \omega_1^2 \cdot \cos^2 \omega_1 t + R_2 \cdot \delta_2^2 \cdot \omega_2^2 \cdot \cos^2 \omega_2 t \\ & + (R_1 + R_2)\,(\delta_1 \cdot \delta_2 \cdot \omega_1 \cdot \omega_2 \cdot \cos \omega_1 t \cdot \cos \omega_2 t) \end{aligned} \qquad (12)$$

Because ω_1 and ω_2 are different frequencies, the last expression between brackets will be zero after averaging or filtering. The first two terms provide exactly the earlier obtained expression for each individual mode, so the correction principle is applicable to two combined modes. It will be clear that the same reasoning can be extended at will to include any number of simultaneous modes.

The compensation as proposed above requires the availability of an appropriate angular rate sensor, which may be problematic. An alternative is to use a second linear accelerometer in the aft end of the model to derive the angular information. The principle is illustrated in Fig. 6.

For the two accelerometers applies (after integration):

$$\begin{aligned} \dot{\tau}_1 &= R \cdot \dot{\rho} \\ \dot{\tau}_2 &= (R - r) \cdot \dot{\rho} \end{aligned} \qquad (13)$$

in which r is the distance between the two accelerometers. The unknown bending radius R can be eliminated, so that the wanted angular rate is given by:

$$\dot{\rho} = \frac{\dot{\tau}_1 - \dot{\tau}_2}{r} \qquad (14)$$

Given the apparent complexity of the problem, the theoretically conclusive compensation is of a startling simplicity. It is in fact amazing that it has been overlooked for so many years.

INSTRUMENTATION

The on-board instrumentation comprises three types of sensors: the inclinometer itself, the sensors for translation and the sensors for rotation.The obvious choice for the inclinometer is a high accuracy servo-accelerometer.

Because of the high dynamic loading -model vibrations in x-direction- it must have a range of 10 or 20 g and an extremely low non-linearity or voltage rectification coefficient. The scale factor stability should be in the .01 % class while the zero stability for +/- .005 deg. is equivalent to 4 ppm FS, which are both very stringent requirements. Only the best inertial grade sensors like the Allied Signal (ex-Sundstrand, ex-Endevco) Q-Flex type QA 3000 come close. In general one should be aware that even a maximum model AOA of 15 deg represents only 1.7 % of the full scale of a 15 g Q-Flex, which translates into extremely high demands on sensor and signal conditioning.

For sensing the translation of the inclinometer in the Z and Y directions perpendicular to its sensitive axis miniature accelerometers should be used. The speed $\dot{\tau}$ can then be obtained by straightforward integration over a frequency range of appr. 1 Hz to 200 Hz. The wideband vibration noise level is very high, therefore the accelerometers should preferably be of the damped type. Within the operational bandwidth the sensitivity should be constant to within 1 % and the phase response should not deviate more than 5 deg. The range should be 10 g to 20 g, with a good overload capability. The numerical example given before for instance results in an acceleration level of 3 g. Units are manufactured by e.g. Kulite, Entran or Endevco.

For assessing the angular rate there are three options: use an angular rate sensor, combine an angular accelerometer with an integrator or apply the solution with a second set of linear accelerometers as discussed earlier. Applying true angular transducers of either type has the advantage that all sensors can be integrated into one 'inertial' package which can be calibrated as a unit. The bandwidth requirements are of course the same as for the accelerometers, i.e. 1 Hz to 200 Hz with good amplitude and phase response. The FS angular rate should be the order of 1 Rad/s.

Unfortunately the few angular rate sensors which are small enough to be mounted inside a windtunnel model all fall short in one or more respects for this application. The Systron-Donner Gyrochip models have a nominal bandwidth of 70 Hz, with a phase shift of 90 deg. at that frequency, only for bigger models they might be appropriate. The Murata Gyrostar units have bandwidth limitations at 7 Hz and 50 Hz. The sensors manufactured by Applied Technology Associates have ranges which are either too low (.1 Rad/s) or too high (1600 Rad/s).

Amazing as it is, angular accelerometers are a rare breed. The ASM series servo units manufactured by Schaevitz are relatively bulky and have a nominal natural frequency of 70 Hz, which is too low. The same applies to the Systron-Donner Fluid Rotor Angular Accelerometer, which has a bandwidth of 45 Hz. Kistler manufactures a piezo-electric sensor which in one small housing of 16*16*11 mm combines a linear and an angular accelerometer. Ranges and bandwidth are appropriate. It must be used with its own signal conditioning housed in a separate box. Two of these units integrated with a Q-Flex linear servo-accelerometer would than constitute the complete inertial package with a size of 50*50*50 mm. This would be a very attractive option for an accurate AOA measurement. There is a good cause for a third sensor, so that all model movements, linear and angular including roll, can be monitored. The angular accelerations are relatively low and are estimated to be of the order of 10 to 100 Rad/s^2, depending on mode and frequency.

PROCESSING

When looking into signal conditioning and -processing a fundamental choice is whether the compensation should be computed by analog or by digital means. It is nowadays perfectly feasible, using Digital Signal Processing techniques, to perform all the filtering, integration and multiplication operations in real-time by digital means after fast A-D Conversion of the input signals.

Because 80 % of the functionality required was already available in analog form from earlier experiments in the field (Ref. 2), NLR opted for the analog route. The existing Inclinometer Conditioning Unit was modified to include two sensors instead of one for each compensation plane and process these by analog means according to the algorithm derived in this paper. The result is then subtracted from the filtered and amplified inclinometer output.

Of course, the model instrumentation will influence conditioning and processing. In particular for the angular sensor the choice is not obvious. Therefore the circuitry in the modified ICM Unit can be adapted to each of the three types of transducers by means of jumpers. A functional block-diagram is given in Fig. 7 (depicting one compensation channel only). In order to avoid data skew all channels feature identical low-pass filters with a cut-off frequency of 1 Hz. In the signal conditioning of the other channels of the Data Acquisition System - e.g. for balances - the same filters are used, so that all data are coherent.

To assure sufficient resolution also at higher angles, the corrected inclinometer signal is digitized by means of a high stability, 17 bit dual-slope ADC. A separate 12 bit ADC and appropriate signal conditioning are included for the temperature channel of the Q-Flex. The ADC outputs and other numerical inputs, such as local g and mechanical angular offset, are routed to a microprocessor which computes the angle with a resolution of .001 degree. The result is sent to a front panel display for bench-top operation and is available in parallel format for read-out by the computer. Maximum update rate is 20 Hz, synchronized with the sampling of the rest of the data system. Since all (Q-Flex) inclinometers have individual coefficients for span and temperature sensitivity these are stored in EPROM's which are addressed by the microprocessor.

CALIBRATION

The AOA system must be calibrated prior to a run under wind-off conditions. This procedure involves four steps:

- Adjustment of inclinometer zero
- Check on inclinometer span
- Adjustment of compensation in X-Z plane
- Adjustment of compensation in X-Y plane

The last two steps are only required in case linear accelerometers are used, because of the model dependent distance r between the two. When true angular sensors are used, in principle only a check is necessary, since there are no model dependent variables in that case.

For setting the inclinometer reading to zero for a reference zero of the model a very high resolution electronic level is used. The offset angle can then be set on thumbwheel switches on the ICM Unit with a resolution of .001 deg. It is subtracted in the microprocessor after computation of the actual inclinometer angle. The combination of a very high precision reference wedge of 5.000 deg and the electronic level then allows a check on the span and thereby on the presence of the correct coefficients for the particular inclinometer.

For adjustment or check of the compensation an electrodynamic shaker is used to excite the model/balance/sting combination. In order to generate sufficiently large amplitudes pure harmonic excitation at some of the natural frequencies is used. The model is excited either directly on the fuselage in front of the balance center, or indirectly via the sting. The latter method produces less amplitude, but avoids influencing the AOA by the shaker. It was used for a proof-of-concept test which is reported on in Ref. 5. Two figures from this report illustrate the procedure: Fig. 8 gives the mechanical arrangement and Fig. 9 some results. The effectiveness of the compensation is clearly demonstrated in this static vibration test. Since the compensation should be independent of the mode, a relevant procedure is to adjust the compensation for one mode and then check its validity for another. Of course this will have to be carried out in two perpendicular planes. Given the presence of appropriate hardware the whole operation is a matter of minutes.

VALIDATION

The proposed compensation technique has been applied in practice during several windtunnel tests in the NLR Transonic HST, using two different models. The model instrumentation relied on the dual linear accelerometer technique for deriving the rotational component. The ICM conditioning unit was adjusted by exciting the model in Z and Y directions as described before. The Eloptopos system was used as a reference for the true AOA. The models used were NLR reference models with a span of appr. 1.2 m.

Figs. 10 and 11 present the differences between the readings from Eloptopos and the compensated Q-Flex during a number of continuous sweep incidence polars. Fig. 10 relates to the wind-off condition and confirms the coherence between the two AOA systems for different Z positions. In fact these data are used as calibration data for Eloptopos. It can be seen that between -2 deg and +8 deg the differences are within ± .005 deg. From other comparison data (not shown here) it can be concluded that the slight scatter is mainly due to the Eloptopos system.

In Fig. 11 wind-on data are given for three polars at Mach numbers of .5, .7 and .75. Disregarding the starting transient at -2.5 deg all data are comfortably within +/- .01 deg. Uncompensated data (not shown here) revealed scatter up to .09 deg under comparable cruise conditions and .16 deg at buffet.

The equipment configuration used during the second test allowed simultaneous recording of compensated and uncompensated inclinometer data. A different model was used and incidence sweeps extended well into the buffet region at times. Only one example is given, because the general pattern is very repeatable. It applies to a 'worst case' scenario in terms of model vibrations which occurred at a Mach number of .765. Bias errors, plotted in Fig. 12, were up to .43 deg at 4 deg AOA. The corresponding deviations of the compensated inclinometer are presented in Fig. 13. The pattern is characterized by: a constant offset of .01 deg, slightly increasing with incidence, combined with a near-perfect compensation of the centrifugal errors. Subsequent inspection learned that the offset was due to play and deformation of the mounting of the GRP nose of the model, which houses one of the infrared LED's for the Eloptopos reference system.

CONCLUSION

A novel scheme for vibration compensation of inclinometers has been devised and validated. It allows to use a small, proven inclinometer in a windtunnel model under adverse conditions and still get very accurate incidence readings. Additional model instrumentation required is small and readily available. Signal conditioning is straightforward, signal processing is indeed special and dedicated, but not very complicated. The compensation is essentially real-time and is compatible with continuous sweep testing. The technique has been validated during tests in a transonic windtunnel at relatively high vibration levels. A dedicated Conditioning Unit is available which produces fully compensated AOA readings with one thousandth of a degree resolution.

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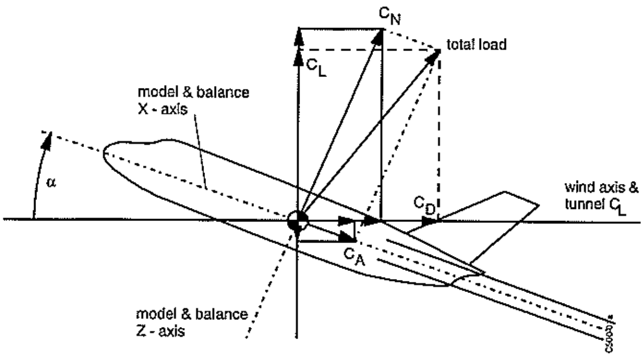

Fig. 1 Aerodynamic axis systems

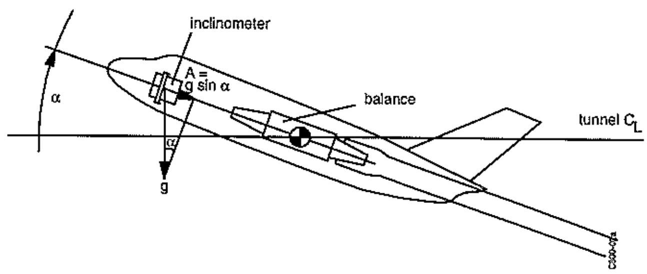

Fig. 2 Model with inclinometer and balance

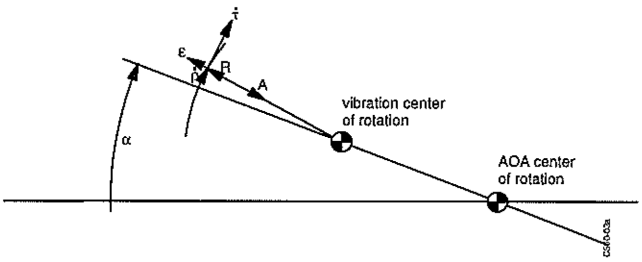

Fig. 3 Centrifugal acceleration error ε

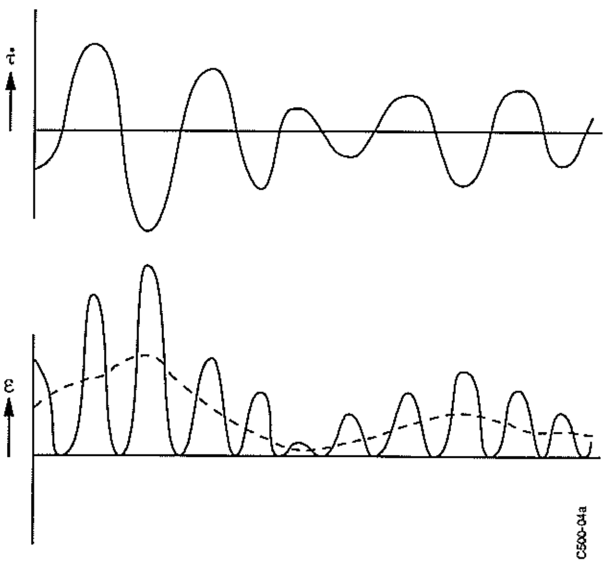

Fig. 4 Quadratic relation between $\dot{\tau}$ and ε

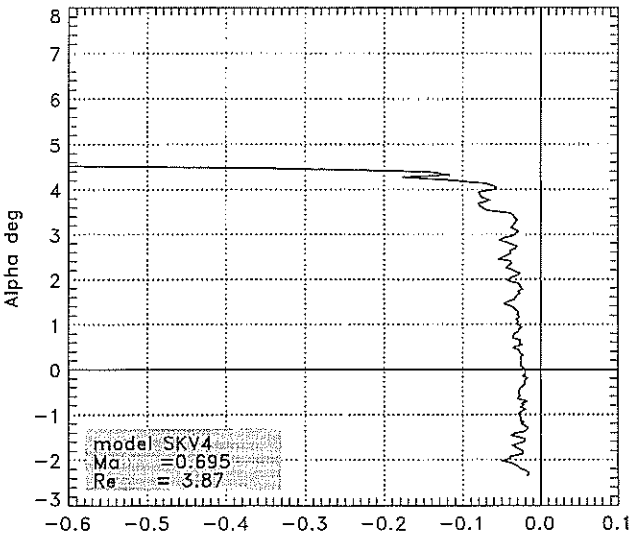

Fig. 5 Continuous Sweep Polar: Δα vs AOA

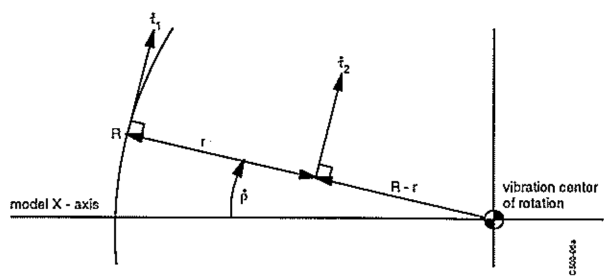

Fig. 6 Compensation using two
linear accelerometers

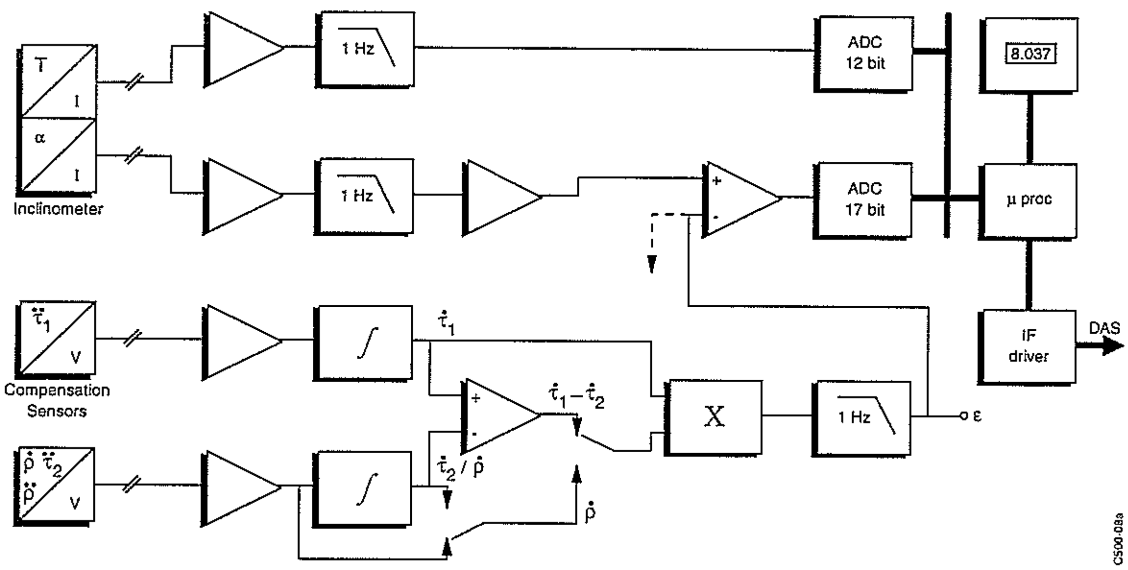

Fig. 7 Block diagram Inclinometer Conditioning Unit

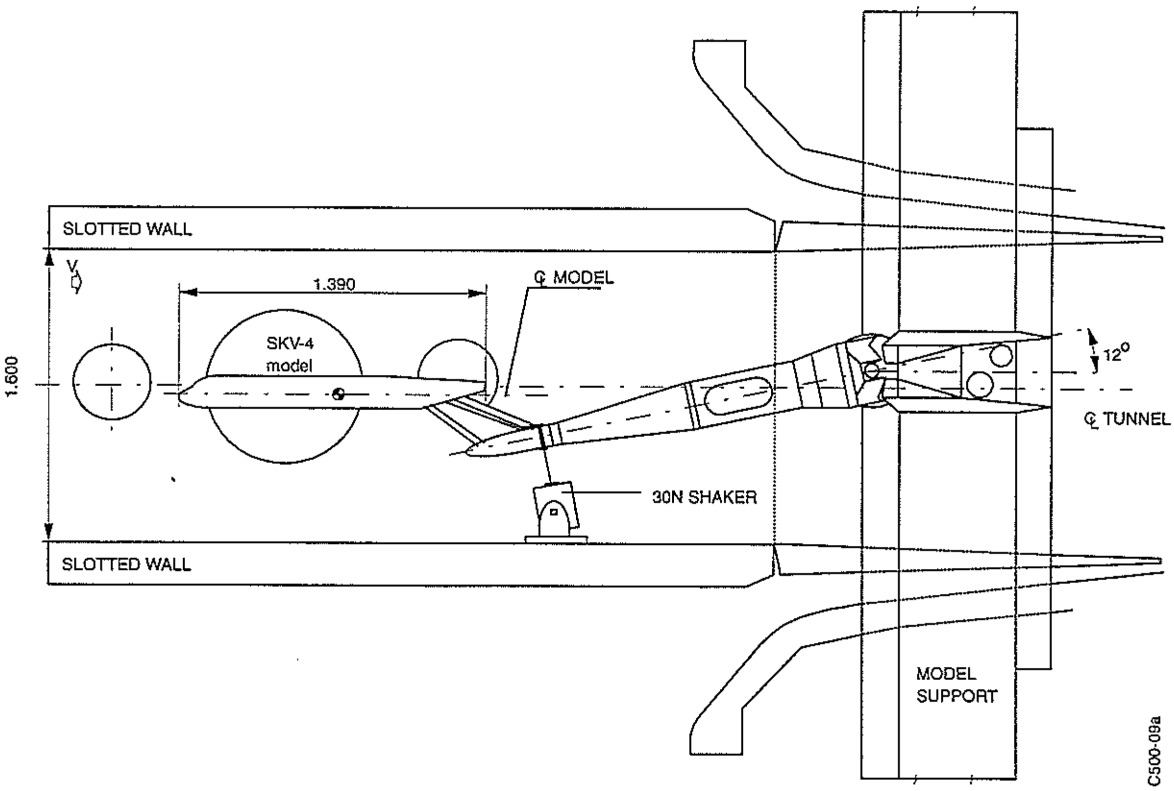

Fig. 8 Static vibration test in HST test section

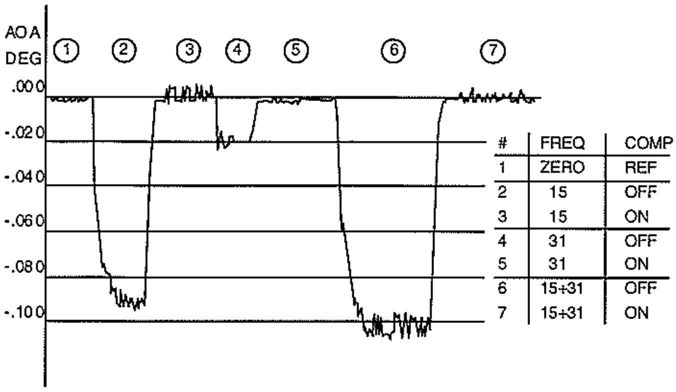

Fig. 9 Wind-off compensation for various modes

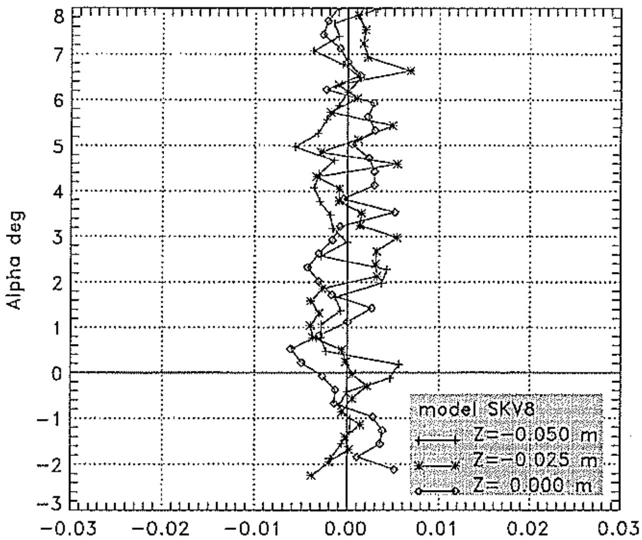

Fig. 10 Wind-off calibration Eloptopos vs Inclinometer

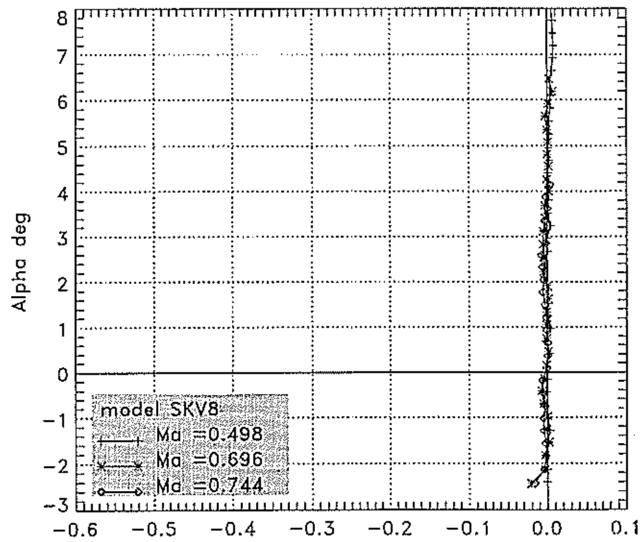

Fig. 11 Compensated Bias Error for 3 Machnumbers

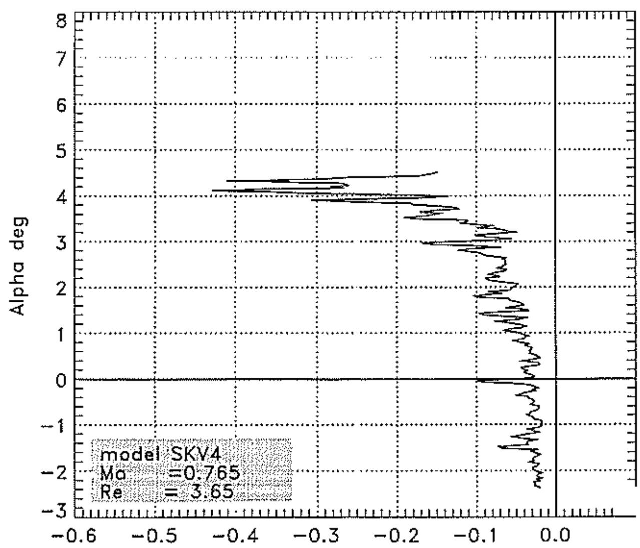

Fig. 12 Uncompensated Bias Error at M=.765

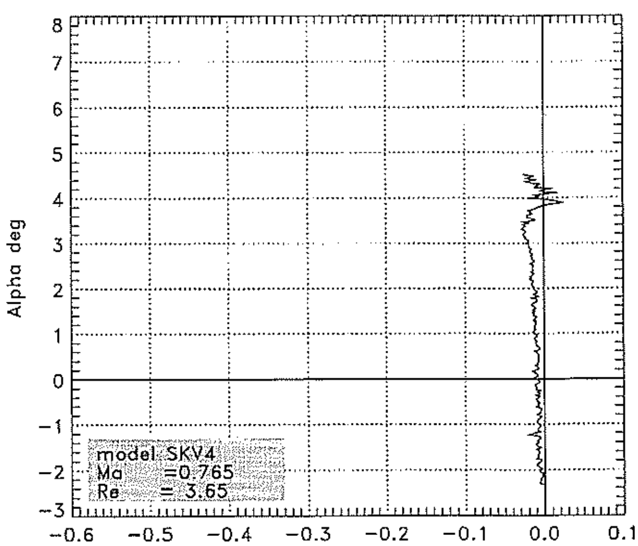

Fig. 13 Compensated Bias Error at M=.765