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Stability and Control Flight Testing - Some of the Test Instrumentation Requirements

by

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SUMMARY

The scope of stability and control flight testing at R.A.E. Bedford and the type of physical measurements are briefly reviewed. Suggested overall accuracies for the quantities, including the effects of transducer/recording element and readout system, are stated. Particular emphasis is put on the need for good instrumentation dynamic characteristics and the need for accurate dynamic calibrations of the instruments. The overall accuracies achieved using photographic trace recording systems is of the order 2% - 3%, whilst 1% is required and exceptionally, for special tests, 0.2%. The use of digital/magnetic tape systems looks attractive to meet these requirements, but flight experience has shown that the potential accuracy of this system may not be achieved. The need for proving new sophisticated instrumentation systems in real flight environments is stressed.

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1 INTRODUCTION

The purpose of this paper is to give some idea, from a flight test engineer's viewpoint, of the instrumentation requirements for stability and control flight testing and to consider some possible developments in the future. The emphasis is put on the instrumentation systems currently used rather than details of flight test techniques and methods of analysis. This approach is adopted since, although the author does not claim to be an instrumentation specialist, through our experience we can claim to know requirements and some of the limitations of present systems.

Our flight test experience relates to work in Aero Flight Division of the Royal Aircraft Establishment, Bedford. The environment is a research one and differs somewhat from that experienced in development flight testing. Most of our research aircraft are small and this severely limits the amount of test instrumentation that can be carried. There is an understandable reluctance on our part to use new and sophisticated, instrumentation systems in our research aircraft until these systems have been thoroughly proved in flight; to act otherwise can very easily lead to the problem of developing and proving the new instrumentation rather than getting aerodynamic information on the research aircraft. For these reasons no doubt some of the instrumentation specialists will consider that our systems are somewhat out-dated. As flight test engineers we can reply that we want a flight demonstration of the very high accuracies and reliabilities claimed for new instrumentation; in our experience such claims are, all too often, not substantiated when these systems are used in flight.

The scope of our work in the stability and control field is quite wide and includes investigations into: measurement of stability derivatives; atmospheric turbulence studies; aircraft vortex wake investigations; V/STOL aircraft; evaluation of new operational aids and techniques such as take-off directors and steep approaches of aircraft; flight testing of free-flying models. The essential point about all these tests is that measurements are made under dynamic flight conditions. Thus it is necessary to have a thorough knowledge of the dynamic response of the instrumentation system both to ensure that the instrumentation is satisfactory and to allow a proper analysis of the flight results.

For most of our quantitative tests we have used photographic trace recorders and manual or semi-automatic readout. However, telemetry has been used on our VTOL aircraft to provide a monitoring system. This can be used for investigations in the event of an accident, to assist in the training of a new pilot and for any special tests where it is useful to have an immediate display on the ground of the aircraft response. The accuracy demand for this type of work is not high - about 5% - and this has been met fairly easily with the use of relatively simple equipment.

When considering the instrumentation requirements, the type and accuracy of the quantities will be considered first, followed by discussions on voltage supplies, transducers, recording systems and readout systems.

2 QUANTITIES TO BE MEASURED AND REQUIRED ACCURACIES

The quantities required in stability and control flight testing can be divided into two broad classes. The first class, which I shall call 'direct', enter into the analysis of the results in a fairly simple and direct manner, and the accuracy of measurement is directly related to the accuracy of the final answer. An example of this type of quantity is the aircraft speed which is required when calculating the dynamic pressure to non-dimensionalise a stability derivative. Further examples of this type of quantity are aircraft height, outside air temperature, engine thrust, fuel state, etc. Measurements of this sort are common to other fields of work, such as performance testing, and the accuracy demanded by the stability and control specialist is no higher, in general, than that demanded by other users, and hence does not pose a particular requirement in these cases. This is not to say that all the 'direct' quantities are measured with sufficient accuracy to satisfy the needs of all specialists: for example, one particular quantity in this class, outside air temperature, is required to a high accuracy for atmospheric turbulence studies; an accuracy of 0.1°C up to a frequency of 3 cps is required and present transducers are incapable of this performance. Another quantity in this class is the airspeed of VTOL aircraft during the hover and transition phase. An accuracy of ±1 knot in the range 0 to 40 knots is required and current aircraft transducers do not perform this well.

The second class of quantities, here called 'indirect', are much more specific to the stability and control specialist and usually his requirements are more demanding than those of other users. Quantities in this class are: aircraft accelerations along the three axes, aircraft rates of rotation about the three axes, angular position in space of the aircraft's axes, angles of incidence and sideslip and control surface positions. In some cases angular accelerations also are required. For most of the 'indirect' quantities an accuracy* of about 1% of the full range of measurements and about 1^{o} in phase angle is required up to a frequency of 3 cps; for turbulence studies the frequency range of interest is up to 10 cps. To enable stability derivatives to be extracted by more sophisticated methods of analysis it is necessary to measure most of the quantities to about 0.2% accuracy up to 10 cps. It is apparent that these demands for accuracy particularly the latter, are severe. It might be wondered why such a high accuracy is demanded. The reason is that the analysis of the indirect quantities usually involves a fairly complex series of operations during which the small errors in several individual measurements have a cumulative effect on the end result; for example, a stability derivative may only be deduced to about 10% even when the accuracy of the basic measurements is about one order better than this. Fig.1 shows an example of some stability derivative measurements made on the Fairey Delta 2 aircraft using a fairly high quality of instrumentation; the accuracy of the measurements is only about ±10%. Whilst some of this inaccuracy is due to limitations of the test technique, improved instrument accuracy would be beneficial. In fact n_v is a relatively easy derivative to measure. An example of a fairly important derivative that is more difficult to measure is the damping in yaw, n_r. Fig.2 shows a vector plot of the yawing moments in a typical Dutch roll oscillation. An error of only 1^{o} in the phase angle between sideslip and acceleration in yaw would cause an error of about 10% in n_r. This phase angle is normally determined from measurements of lateral acceleration at the aircraft centre of gravity. Normally it is not possible to site an accelerometer at the centre of gravity of the aircraft, in which case kinematic corrections must be made for the rolling and yawing motion of the aircraft. These corrections can be quite large, Fig.3 showing a correction of 60^{o} in phase when the accelerometer is displaced 2.1 ft forward and 1.7 below the aircraft centre of gravity. The position of the accelerometer can be determined with accuracy, but the correction also involves values of rates of roll and yaw. To determine the phase angle correction to 1^{o} requires that the phase and amplitudes of the roll and yaw rates are known to at least an accuracy of 1^{o} and 1% respectively. Thus quite small errors in the measurements of lateral

*The accuracies quoted here relate to the system as a whole, i.e. the combination of transducer, recording element, and readout system.

acceleration, rate of roll and yaw could lead to significant errors in deducing n_r.

Typical ranges of the quantities essential to stability and control work are shown in Table 1. Although in general this variety of ranges is needed to accommodate the spectrum of modern aircraft, it is not unusual to find that more than one range may be needed to accommodate different tests in a given aircraft and, from the flight test engineer's viewpoint, it is highly desirable that changes of sensitivity should be practicable without the need to change instruments and recalibrate.

3 VOLTAGE SUPPLIES AND TRANSDUCERS

Stabilised voltage supplies, both dc and ac, are required for some instrumentation purposes. For example if the output from a transducer is recorded on a galvanometer the signal will be sensitive to supply voltage. It is possible to monitor voltage variations, but it is preferable that the supply be stabilised. AC supplies are normally used to drive rate gyroscopes and thus it is important that the frequency should be stabilised as well as the voltage; the supply must also be free from noise. The voltage and frequency should remain within 0.5% of reference values although for some special tests 0.2% is required. Experience shows that this performance is often not attained.

The calibration of the transducers should be linear as this can simplify considerably the analysis of the data, particularly if computers are being used. For some tests of a qualitative nature strict linearity is not required, but in these cases non-linearities should not exceed 5% as the resulting distortions to the traces makes it very difficult to interpret the records visually.

Experience has shown that it is highly desirable that the transducer dynamics can be described by a simple second order differential equation of the form:

$$m \ddot{x} + k \dot{x} + c x = \text{Forcing function} \qquad (1)$$

The coefficients of this equation are constants and the three terms represent inertial, damping and stiffness terms respectively. The solution of this equation shows that the system has a unique natural frequency and damping ratio. If the forcing function has a sinusoidal form b sin ωt then the response, x, will be of the form

$$x = A\,b\,\sin(\omega t + \phi) \qquad (2)$$

Thus the input is modified by an amplitude ratio A and displaced in phase by ϕ. For a given second-order system, A and ϕ depend only on the frequency, ω, of the input.

The damping ratio of a transducer should be close to 0.7 of critical since the amplitude ratio then remains very close to unity for input frequencies below about 40% of the transducer's natural frequency, ω_n. Thus a complex waveform, consisting of the summation of many frequencies (below 0.4 ω_n), can be recorded without significant distortion. The advantages of a high transducer natural frequency in certain applications will be obvious. Also it is desirable that the phase lag and amplitude ratio variations with frequency for all the transducers should be similar as this then avoids the need to apply instrument dynamic corrections. This condition will only be satisfied if all the transducers have similar natural frequencies and damping ratios.

In practice transducers do not behave as the perfect model described by equation (1). A common cause is that the damping may not be strictly proportional to velocity; this occurs, for example, if the damping is provided by viscous effects in an air or oil dashpot. In this case the damping will vary with environmental changes of temperature or pressure. Another cause of departures from the perfect model of equation (1) is the presence of friction or backlash in the transducer; such effects are introduced if a potentiometer is used to measure, say, the displacement of a mass in an accelerometer or if linkages are present in the transducers. (A potentiometer also gives a poor resolution adversely affecting the accuracy.)

When non-linear effects of these types are present the simple solution (2) to a sinusoidal input no longer applies. In fact calibrations confirm that the amplitude ratio A and phase angle ϕ vary with the amplitude of the input, and consequently the output of the transducer may be seriously distorted. Such effects make it impossible to analyse dynamic flight records satisfactorily.

For these reasons it is essential that dynamic calibrations of all transducers are made in the laboratory. These calibrations will reveal if the instruments are satisfactory for use in dynamic flight tests and supply the data for transducer response corrections. Satisfactory laboratory calibrations are in themselves not easy to perform, as there is a requirement in stability and control work to know the phase lags of transducers to at least 1° and this is probably beyond the resolution of most methods of calibration currently used.

Experience with most transducers in current use has shown that, at best, their accuracy is about 1% of the full range. This is not sufficient to meet the required overall accuracy of 1% mentioned in section 2 when it is remembered that this figure must include recording and readout accuracies in addition; it is quite inadequate for the accuracy of 0.2% mentioned in section 2 for some special tests.

One variety of transducer that is currently available is based on the force-balance principle and offers a high potential accuracy (0.1% or better). However there are some serious disadvantages in using force-balance instruments in the vibratory environments present in many aircraft. Such transducers have high natural frequencies and respond readily to local vibrations of the aircraft's structure as well as to the aircraft's overall motion, thus the signal of interest to the flight dynamicist may be swamped by structural noise. Electrical filters can be used to reduce this noise, but often their use introduces other, more subtle, difficulties. Cases have been observed where the response of the transducer to vibrations was sufficient to saturate it; in this case a filter would be completely useless. The sensitivity of instruments to vibration is of particular importance in VTOL aircraft where the vibration levels are usually rather high.

Incidence and sideslip, which may be sensed by null seeking vanes or a suitably calibrated pressure probe, are particularly difficult to measure to the accuracies required. The problem here is essentially that of determining the corrections to be applied to the sensor readings which, of course, are subject to distortions associated with the flow field around the aircraft on which the sensor is mounted.

4 RECORDING AND READOUT SYSTEMS

The systems with which we are most familiar have employed trace recorders using galvanometers or ratiometers as the recording elements. These recorders have the advantage that they are robust, relatively simple, reliable, and provide records in an analogue form; this last feature is invaluable to the flight test engineer for "quick look" editing prior to more detailed analysis. Any unsatisfactory records can be rejected immediately and so prevent the waste of analytical effort that sometimes occurs with more sophisticated recording systems that lack a "quick look" facility. The disadvantages of trace recorders are the limited number of channels per unit volume, limited accuracy and relatively cumbersome readout. The accuracy loss on recording is assessed as 1% with a further 1% loss on readout using either manual or semi-automatic methods. Assuming a figure of 1% accuracy for a typical transducer, taking the rms of all the sources of error gives an overall accuracy of about 1.7% using this system. Frequently the errors quoted for the constituent parts are larger than 1%, and thus an overall accuracy of only 2 - 3% may be achieved in practice.

5 ASSESSMENT OF THE PRESENT POSITION AND FUTURE TRENDS

It is apparent that the use of photographic trace recording systems, with overall accuracies probably of the order of 2 - 3% are not satisfactory for stability and control work. The present trend in the analysis of stability and control flight tests is to use more sophisticated methods of analysis in an attempt to extract more data. However, experience with these methods show that they cannot produce better results than the more simple methods unless the accuracy of the data acquisition system is improved. The immediate aim should be to improve the overall accuracy to 1% with a longer term aim of achieving 0.2%. How are these better accuracies to be achieved? It is almost certain that the accuracy of recording and readout of photographic trace recorders cannot be improved significantly, and since these represent a significant proportion of the overall inaccuracies, some better form of recording must be used. The use of magnetic tape systems looks very attractive, particularly as they have the potential of being able to record a large amount of data per unit volume, and the signal is recorded in an electrical form making it very suitable for automatic computing processes. Very high accuracies have been claimed for some of the more sophisticated digital/magnetic tape systems. Possibly we have not been very lucky, but we have yet to see these accuracies demonstrated with an actual installation in flight. No doubt the accuracies claimed will be achieved, but it seems that more development work is required in this field. Magnetic tape recording systems should always be able to produce an analogue record, of limited accuracy, for "quick look" purposes.

The use of telemetry as a data acquisition system should be reconsidered. The accuracy claimed for modern telemetry systems is very high and if realised in practice, telemetry could be used in conjunction with a ground-based magnetic tape recorder.

The accuracy of transducers will also have to be improved if we are to achieve the stated requirements of accuracy.

The flight test engineer is in somewhat of a dilemma. He wants to use the more advanced data acquisition systems being offered by the instrumentation engineer, but hesitates because past experience suggests that he will become involved in developing the instrumentation system at the expense of the aircraft. The crux of the problem seems to be that the new data acqusition systems are being developed in the laboratory but insufficient effort is being made to prove these systems in real flight environments. The example already quoted of the difficulties of using a force-balance accelerometer in an aircraft in the presence of vibrations illustrates one facet of the problem. Clearly more effort should be devoted to the flight proving of complete instrumentation systems.

Table 1

TYPICAL RANGES OF QUANTITIES REQUIRED IN STABILITY AND CONTROL FLIGHT TESTS

Quantity	Maximum range	Quantity	Maximum range
	±0.1 g		±10°
Acceleration	±0.25 g	Heading	±30°
	±0.5 g		±180°
	±1.0 g		
	0 g to 2 g		
	0.5 g to 1.5 g	Angular acceleration	±20°/sec^2
	-1.0 g to 5.0 g		
Rate of rotation	±5 deg/sec		
	±10 deg/sec		
	±30 deg/sec		
	±45 deg/sec		
	±90 deg/sec		
	±300 deg/sec		
Incidence	±5°		
	0° to 10°		
	-5° to 25°		
Sideslip	±5°		
	±10°		
	±20°		
	±50° } VTOL		
	±90° } VTOL		
Pitch attitude	±20°		
	±40°		
	-10° to +30°		
	-30° to +60°		
Roll attitude	±30°		
	±45°		

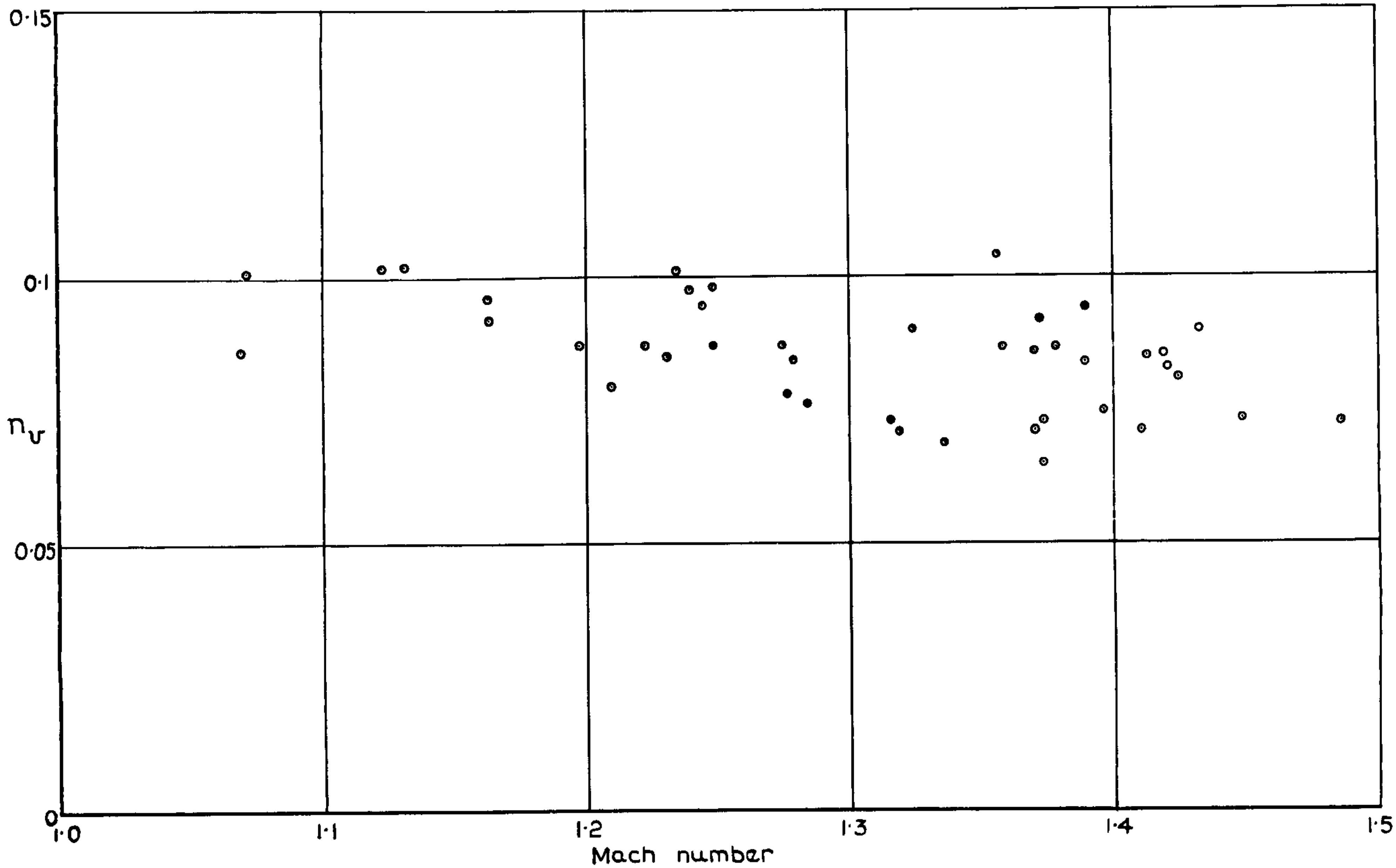


Fig. 1 Variation with Mach number of the directional stability derivative n_v, of the Fairey Delta 2 aircraft, obtained using time vector analysis

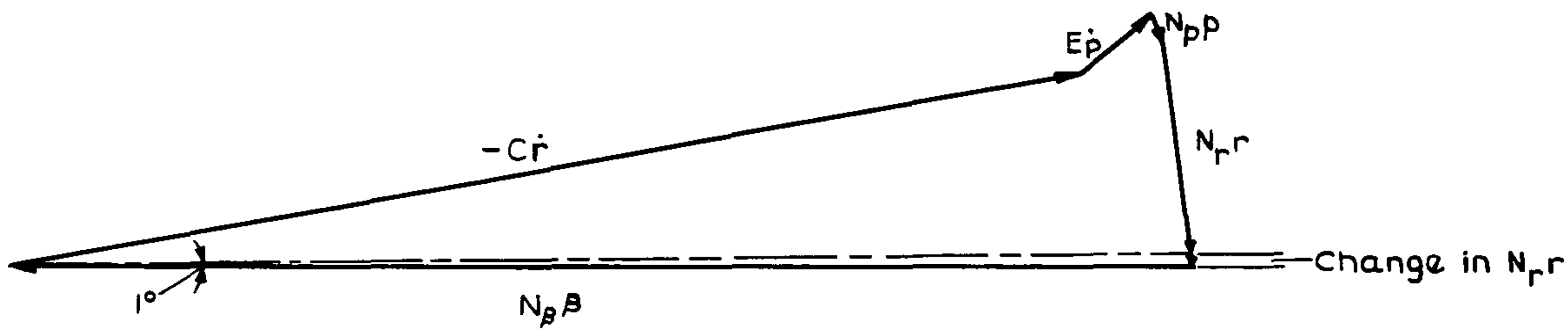
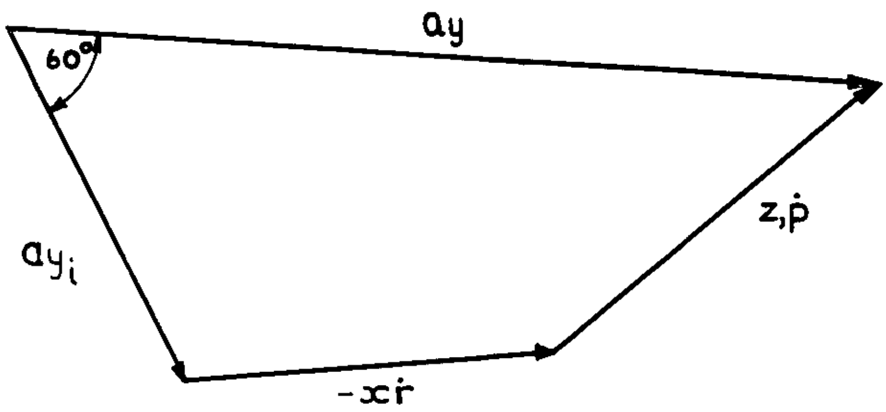


Fig. 2 Yawing moment vector polygon showing change in N_r due to a 1° phase change in angle of sideslip



$x = 2 \cdot 1$ ft
$z = 1 \cdot 7$ ft

a_{y_i} = Measured lateral acceleration
a_y = Lateral acceleration at the aircraft centre of gravity

Fig 2 Transformation of measured values of lateral acceleration to

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