

Netherlands organization for applied scientific research



IZF 1989-24

J.T. Marcus

TNO Institute for Perception

P.O. Box 23 3769 ZG Soesterberg Kampweg 5 3769 DE Soesterberg, The Netherlands Fax +31 3463 5 39 77 Phone +31 3463 5 62 11

-3367

#### INFLUENCE OF GRAVITO-INERTIAL FORCE ON VESTIBULAR NYSTAGMUS IN MAN

18

Nothing from this issue may be reproduced and/or published by print, photoprint, microfilm or any other means without previous written consent from TNO. Submitting the report for inspection to parties directly interested is permitted.

In case this report was drafted under instruction, the rights and obligations of contracting parties are subject to either the 'Standard Conditions for Research Instructions given to TNO' or the relevant agreement concluded between the contracting parties on account of the research object involved.

¢ TNO



#### Classifications:

Copies: Number of pages:	50 26	Report: Title: Abstract:	unclassified unclassified unclassified
		Abstract:	unclassified

# DISTINUTION STATEMENT A

Approved for public release; Distribution Unlimited



CONTENTS

APPENDIX D Programs

ABSTRACT					
ACKNOWLEDGMENTS					
SAMENVATTING	6				
1 INTRODUCTION	7				
2 CENEDATION OF +C CDAVITOINEDTIAL FORCE	7				
2 GENERATION OF $+\sigma_2$ GRAVITOINERTIEL FORCE	7				
2.1 $\mathbf{F}_{\mathbf{g}}$ force in the centrifuge	/ 0				
2.2 +Gg force in an alreratt	0				
3 VESTIBULAR NYSTAGMUS DATA	9				
4 OTOLITH MODULATION OF THE VESTIBULO-OCULAR REFLE	EX ARC 14				
4 1 The velocity storage model	14				
4.2 Extension of the model with an otalithic input	16				
4.2 Extension of the model with an otorithic input	10				
5 DISCUSSION	18				
6 IMPLICATIONS FOR THE AVIATOR IN HIGH PERFORMANCE	E AIRCRAFT 19				
7 CONCLUSIONS	20				
REFERENCES	21				
APPENDIX A Centrifuge mechanics	22				
APPENDIX R Models of the stalithe and the cumula-and	dolymph system 23				
APPENDIX C Final model in a THISIM diagram					
UPPERSANT A TITUT WAAAT TI G TATATI ATGPE CO	23				

Page

26

ï

Report No.:	IZF 1989-24		
Title:	Influence of gravitoinertial force on vesti bular nystagmus in man		
Author(s):	Drs. J.T. Marcus		
Institute:	TNO Institute for Perception TNO Division of National Defence Research Group: Audiology		
Date:	July 1989		
HDO Assignment No.:	A88/M/318		
No. in Program of Work:	732.4 (POW 1988-1991)		

#### ABSTRACT

1

-The influence of high +Gz gravito-inertial force (- G load) on the vestibular system in man has been investigated in a centrifuge with a freely swinging gondola. The vertical vestibular nystagmus induced by acceleration to 3G was analysed, and compared with reference measurements at 1G. Our results indicate that the effects of increased G load are expressed in a prolonged time contant of the upbeat nystagmus, and in a subject-dependent persisting component of this nystagmus.

In an attempt to explain these findings, a current model on the generation of vestibular induced eye movements is extended:

Angular acceleration stimulates the semicircular canals, which in an existing model induce slow compensatory eye movements via a direct reflex path, as well as through an integrating network in the central vestibular nuclei. This model is extended with the G load as a stimulus function for the otoliths, which are influencing eye movements via a direct path, as well as through a modulating action on the central integrator.

This influence of G load on the vestibular system could interfere desorientation. Netter 10 : 12. (AU) with visual perception, and thereby play a role in inducing spatial

#### ACKNOWLEDGMENTS

The cooperation of Maj. C.R. Van Holten, FS, Chief Medical Services, RNLAF, Twenthe AFB, is highly appreciated. The centrifuge experiments were performed at the National Aerospace Medical Centre, Soesterberg, The Netherlands. Ir. R.J.A.W. Hosman from Delft University of Technology has kindly provided us with flight facilities in a laboratory aircraft.

Rap.nr. IZF 1989-24,

Instituut voor Zintuigfysiologie TNO, Soesterberg

<u>Invloed van hoge +G, gravito-inertiaal kracht op de vestibulaire</u> nystagmus bij de mens

J.T. Marcus

#### SAMENVATTING

De invloed van hoge +Gz gravito-inertiaal kracht (= G kracht) op het vestibulaire systeem van de mens is onderzocht in een centrifuge werkend met een vrij uitzwaaiende gondel. De verticale vestibulaire nystagmus geïnduceerd door acceleratie naar 3G werd geanalyseerd, en vergeleken met referentiemetingen bij 1G. Onze resultaten geven aan dat de effecten van toegenomen G-belasting tot uiting komen in een verlengde tijdconstante van de nystagmus met snelle slag naar boven, en in een proefpersoonafhankelijke blijvende component van deze nystagmus.

In een poging om deze bevindingen te verklaren, wordt de generatie van vestibulair geïnduceerde oogbewegingen modelmatig beschreven:

De hoekversnelling stimuleert de halfcirkelvormige kanalen, die volgens een gangbaar model langzame compensatoire oogbewegingen induceren zowel langs een directe reflexbaan, als via een integrerend netwerk in de centraal vestibulaire kernen. Dit model wordt uitgebreid met de G-belasting als stimulusfunctie voor de otolieten, die de oogbewegingen beïnvloeden zowel langs een direct pad als via een modulerende werking op de centrale integrator.

Deze invloed van G-belasting op de evenwichtszin zou de visuele waarneming kunnen verstoren, en een rol kunnen spelen bij het ontstaan van ruimtelijke desoriëntatie.

#### 1 INTRODUCTION

Flight maneuvres in high performance aircraft are capable of generating high acceleration forces. The effects of these forces on the vestibular system are still largely unknown.

The aim of the present study is to evaluate the influence of sustained high +Gz gravito-inertial force (= G load) on the vestibular system. 1 G denotes the amplitude of gravity force in the absence of centrifugal forces, and the index z refers to the subject's head to foot axis.

Previous reports indicate that increased G-load enhances the vestibular sensitivity: Gilson et al. (1973) observed that subjects perceived illusory changes in aircraft attitude, during and after head movements in a 2 G bank and turn. These shifts in apparent orientation are attributed to a G-excess effect. Gillingham and Wolfe (1986) described the mechanism of the G-excess illusion by analysing the displacement of the otolithic membranes during increased G-load. DiZio et al. (1987) reported an increased sensitivity to Coriolis stimulation during the 2 G phase of parabolic flight.

These observations cannot be explained completely with current models of the vestibular system, which do not include variations in G-load. In our experiment the vestibular function was evaluated by investigating the vertical nystagmus induced by the movement of a centrifuge gondola. These eye movements could have practical implications: incomplete suppression will lead to impaired visibility of instruments.

## 2 GENERATION OF +G, GRAVITOINERTIAL FORCE

# 2.1 <u>+G<sub>z</sub> force in the centrifuge</u>

The  $+G_z$  acceleration was generated by means of a centrifuge with radius of 4 m, located at the National Aerospace Medical Center, Soesterberg, The Netherlands. The centrifuge has a freely swinging gondola, so that the test subject within the gondola experiences a zaxis acceleration that is aligned with the resultant of the centripetal and gravitational accelerations. This is called a coordinated turn. The computer-controlled G profile was:

```
orbit1.05 \ G_zfor 1 minacceleration+0.1 \ G_z/ssustained3 \ G_zfor 2 minutesdeceleration-0.1 \ G_z/sorbit1.05 \ G_zfor 1 min.
```

The orbit interphase has been applied in order to reduce the Coriolis stimulation in acceleration and deceleration due to the swing movement of the gondola. At 1.05  $G_z$  the gondola swing angle in roll is already:  $\arccos(1/1.05) = 17.75$  dg.

Nine naive volunteers were exposed to this profile. Prior to the experiment, routine medical examination was performed and the subjects were made familiar with the experimental conditions. The subject wore an anti-G suit, and his head was supported in each of these positions: upright, 40 dg backward, and 90 dg backward. Eye movements were registered by means of infrared photodiodes and phototransistors (Reulen et al. 1988), in complete darkness as well as with visual fixation.

A pilot study was performed on a rotating chair, with the subjects (n=10) lying on their side to stimulate the vertical semicircular canals. The rotation profile was: acceleration at 5 dg/s<sup>2</sup> to an angular velocity of 90 dg/s that was maintained for 90 s before deceleration at 90 dg/s<sup>2</sup>.

# 2.2 <u>+G<sub>z</sub> force in an aircraft</u>

In an aircraft the  $+G_z$  force is generated with a linear velocity that is considerably higher than in the centrifuge. As a consequence, the angular velocity in the aircraft is significantly less than in the centrifuge, when the same G profile, as applied in the centrifuge, is generated in the air.

In Table I a  $3G_z$  coordinated turn is described for the centrifuge, and an aircraft with air speed 150 kts; r - radius, v linear velocity,  $v^2/r$  - centripetal acceleration  $[m/s^2]$  and v/r - angular velocity [rad/s]. In the Table angular velocity is converted to dg/s. radius velocity angular velocity [m] [m/s] [dg/s] centrifuge 4 10.53 151 aircraft 214 77 21

Table I Comparison of a  $3G_z$  coordinated turn in centrifuge and aircraft.

Therefore high G turns in an aircraft experiment will provide further evidence for pure G effects on the vestibular system, because the angular velocity is not as dominant as in the centrifuge. Vertical nystagmus was measured in 3 subjects during a  $3G_z$  level bank and turn; air speed was 150 kts (1 knot = 1.85 km/h).

#### 3 VESTIBULAR NYSTAGMUS DATA

Our findings on the vertical vestibular nystagmus in the centrifuge included:

- (1) The upbeat nystagmus induced by the angular acceleration to  $+3G_z$ had a longer decay time constant in slow phase velocity (spv), than the downbeat nystagmus after deceleration to  $+1G_z$ .
- (2) In 6 subjects a persisting upbeat nystagmus was observed during the  $+3G_z$  load at constant angular velocity of the centrifuge. In pilot studies this nystagmus extended for up to 5 min.

Data from one subject are presented in Fig. 1, showing the G load and the vertical eye position over time. Note that the upbeat nystagmus was still present at the end of constant G load, and that its direction was reversed during deceleration.

A nystagmoid eye movement is composed of a slow compensatory phase, induced by the vestibular system, and a fast phase induced by the saccadic system in order to bring the eyes back in neutral position. This study is focussed on the output of the vestibular organs; therefore the nystagmus slow phase velocity (- spv) is derived from the eye position data which are partly presented in fig 1.



Fig. 1 Plots of  $G_z$  and the vertical eye position signal in a 1-3-1 $G_z$  centrifuge run in acceleration and deceleration phases. A sustained 3G load was applied for 2 min. Note that the upbeat nystagmus was still present after 2 min. During deceleration the direction of nystagmus was reversed.

Fig. 2 shows the nystagmus spv calculated from the eye-position signal. The noise in the spv signal, prior to and after the G run, was caused by the normal resting activity in the eye movements.



Fig. 2 Plots of  $G_z$  and the vertical nystagmus slow phase velocity (spv), corresponding with the dataset in Fig. 1. Note that the time constant of recovery from the upbeat nystagmus during  $3G_z$  is longer than for the downbeat nystagmus after deceleration to  $1G_z$ . The persisting vertical upbeat nystagmus during the  $3G_z$  load has a magnitude of about 10 dg/s.

The nystagmus time constant,  $T_c$ , was determined by fitting an exponential of the form spv - A\*exp(-t/ $T_c$ ) to the decaying part of the slow phase velocity, using the algorithm described by McFall et al. (1986). The spv of the sustained nystagmus was subtracted from the data prior to calculating the best fit equation. In Table II the computed values of  $T_c$  for the acceleration and deceleration phases are presented. Two subjects were exposed to a different G profile, so the time constants for their responses are not included.

Subjects	Head position backw. [dg from vertical in sagittal plane]	Time constant from 1 to 3G <sub>z</sub> [s]	Persist. during <sup>3G</sup> z	Time constant from 3 to 1G <sub>z</sub> [s]
kre	40	10.8	+	7.5
kre	90	8.5	+	8.0
ott	90	13.3	+	10.3
vos	90	10.6	+	7.9
mag	0	12.6	+	8.7
mag	90	10	-	9.7
gra	0	17.8	-	3.5
gra	40	21.1	+	3.6
gra	90	15.5	+	7.3
vee	0	27	+	4.8
vee	40	7.4	+	3.1
vee	90	21.1	-	5.6
ble	0	13	+	13.4

Table II Decay time constant of vertical nystagmus induced by centrifuge acceleration from 1 to  $3G_z$ , and deceleration from 3 to  $1G_z$ . A "+" indicates the observation of persisting upbeat nystagmus during the  $3G_z$  load.

Application of a sign test results in the conclusion that the time constant after G onset is longer than after G offset, with p < 0.005. Suppression of the vertical nystagmus could be achieved by fixation on a stationary visual target within the gondola. However, during G onset and G offset this suppression was not complete, and nystagmus amplitude amounted up to 5 dg/s in spite of visual fixation. Dependence on pitch head position has not been found so far.

A prolonged decay time constant is observed after G onset, when comparing it with the decay after G offset with the same rate. Before this can be attributed to the G load, the first to check is the symmetry between up-and downbeat nystagmus.

When the subject in the centrifuge is facing forward with respect to the direction of rotation, then an upbeat nystagmus is generated at G onset, and a downbeat at G offset. If there would exist a physiological asymmetry with the upbeat nystagmus inherently longer during than the downbeat, then the observed prolongation of time constant after g onset is no G effect, but merely an expression of this natural asymmetry. The up-down symmetry of vertical nystagmus at 1G was therefore investigated by positioning subjects on their side on a rotating platform. More detailed analysis will be presented in the near future.

The results of the pilot study on the rotating platform were:

- (1) No asymmetry in vertical upbeat or downbeat nystagmus was observed.
- (2) The decay time constant of vertical nystagmus was in the order of 4 s.
- (3) The duration of nystagmus coincided with the duration of motion perception.

These data indicate no physiological up-down asymmetry; the observed prolongation and sustained component of upbeat nystagmus in the centrifuge should therefore be attributed to the Gz load. In addition, vertical nystagmus could give information about the subject's motion perception.



Fig. 3 Gravity load and vertical nystagmus slow phase velocity (spv) observed in a Beaver aircraft during a coordinated turn with a maximum load of  $2.6G_z$ . Peak angular velocity in the pitch semicircular canal amounts to about 16 dg/s. Note the persisting vertical upbeat nystagmus during the G load, and the absence of downbeat nystagmus during G offset. Data are from the same sensitive subject, whose response in the centrifuge is shown in Figs. 1 and 2.

Further evidence for pure G effects can be found by flying the centrifuge G profiles in an aircraft: a G stimulus with considerably less angular acceleration (see table 1). Peak G load in this aircraft run was 2.6 G with air speed 150 kts, corresponding with angular velocity of 17.5 dg/s, and angular velocity in the pitch semicircular canal of 16.1 dg/s. The persisting upbeat nystagmus was observed in one of the 3 subjects tested; see fig. 3. In the other subjects registration failed due to motion sickness, or a technical problem. Although the measurement refers to one subject, it does confirm the existence of a pure G induced upbeat nystagmus in sensitive subjects.

#### 4 OTOLITH MODULATION OF THE VESTIBULO-OCULAR REFLEX ARC

#### 4.1 <u>The velocity storage model</u>

In order to evaluate the observed characteristics of vertical nystagmus in the centrifuge, the processing of angular velocity information was computer-simulated on the basis of the velocity storage model (Raphan et al., 1977; Cohen et al., 1977; Raphan et al., 1979).

The questions to be answered by means of model simulation were:

- (1) Is the prolonged duration of nystagmus induced by acceleration, compared with deceleration, merely an effect of the non-linear angular acceleration trajectory of the stimulus to the vertical semicircular canals?
- (2) Could the sustained vertical nystagmus under gravity load be explained by otolith stimulation, either by a direct path from the otoliths to the oculomotor system, or by a conditioning effect on the discharge time of the velocity storage mechanism?



In Fig. 4 the vestibular branch of the model is presented:

Fig. 4 The velocity storage model for the vestibular nystagmus (Raphan et al., 1979). The cupula dynamics are presented in more detail in Appendix B and Fig. 8. The cupula deflection signal is transmitted over the direct vestibular pathway, and is also coupled to the central integrator via the forward gain element g; the integrator discharges via the feedback gain element h. Values used in the model are h = 0.15 and g = 0.2. In the model calculations for the vertical nystagmus, the head velocity input was the pitch angular velocity profile in the centrifuge (Appendix A).

The head velocity input will be the pitch angular velocity profile, which can be calculated for the coordinated turn of the centrifuge gondola, based on the linear G profile of 0.1  $G_z/s$  (Appendix A). Details of cupula dynamics are given in Appendix B. The slow compensatory phase of nystagmus is generated by the sum of two components: a direct pathway from the semicircular canals, and an indirect pathway through an integrator or storage mechanism localised in the central vestibular nuclei. It is assumed here that a similar storage mechanism is utilized in generating vertical as well as horizontal nystagmus. The value of the feedback gain element for vertical nystagmus is estimated to be h = 0.15. Displayed in Fig. 5, from above downwards, are: the stimulus function, the model predictions for the cupula dynamics, the central integrator, and the resulting slow phase velocity.



Fig. 5 Model predictions evaluated by means of the velocity storage model in Fig. 4, during a  $1-3-1G_z$  centrifuge run with linear onset and offset rates of 0.1  $G_z/s$ . Note the non-linear angular velocity profile of the stimulus to the vertical semicircular canals (upper trace). The output is displayed from: the cupula dynamics, the central integrator, and the final summator which determines the nystagmus slow phase velocity (spv). It is shown that during deceleration the peak outputs from cupula and integrator almost coincide, resulting in maximal spv induction during G offset.

The high nystagmus amplitude during G onset and G offset is caused by the angular acceleration and deceleration respectively of the centrifuge, and thereby initiated by semicircular canal stimulation. During deceleration the cupula gets its peak stimulation when it is already deflected, resulting in a sharply peaked response. In addition, during deceleration the outputs from cupula and integrator reach their maxima almost simultaneously, resulting in a maximum nystagmus generation during deceleration in the downbeat direction.

#### 4.2 Extension of the model with an otolithic contribution

These model calculations however, do not predict a prolonged nystagmus time constant during G load on the basis of canal output alone. Neither is a persisting nystagmus predicted during steady G load, because the angular velocity is constant. Because the otoliths are the

sensors for linear acceleration, an extension of the velocity storage model is proposed in which an input from the otoliths make a contribution: see Fig. 6. Gravity acts as a second component of the stimulus function. A simplified model for otolith dynamics is presented in Appendix B.



Fig. 6 Extension of the velocity storage model with gravity load as a second component of stimulus function. The gravity signal enters the otolith dynamics, and is then transferred to nystagmus velocity with the slow phase in downward direction (2). Otolith output also influences the feedback factor in the central storage integrator, leading to a prolonged time constant (1).

It is suggested that the direct otolith path (2) is responsible for generating the persistent nystagmus component during the G load. However, in order to explain the asymmetry between acceleration and deceleration response another mechanism must be added. It is proposed that the otoliths modulate the feedback gain element h of the central storage integrator and consequently the discharge time constant 1/h. Displayed in Fig. 7 are: angular velocity in vertical canal, gravity load, output of central integrator and resulting spv. Cupula output is the same as in Fig. 5.



Fig. 7 Model predictions of the velocity storage model with gravity load as a second stimulus function. Cupula output, not shown in this plot, is identical to that in Fig. 5. The differences with the spv trace in Fig. 5 are: an increased decay time constant during the G load, and a persisting component. This results in a better approximation of the centrifuge data presented in Fig. 2.

Comparison of the spv model prediction in Fig. 7, and the spv data in Fig. 2, indicates that the extended model can account for both the asymmetry in spv response and the sustained nystagmus at constant velocity.

#### 5 DISCUSSION

Previous studies have been devoted to potential physiological asymmetries in vertical eye movements: Matsuo et al. (1979) observed an asymmetric velocity storage for upward and downward nystagmus in monkeys: the amount of stored activity was always weaker for upward than downward nystagmus. However, if a similar asymmetry exists in man, it cannot explain our finding of a prolonged upbeat nystagmus.

Baloh et al. (1986) found no significant difference between the mean gain of up and down slow eye movements induced by vestibular, visual or visual-vestibular stimulation in a group of normal human subjects. This is in agreement with the results of our pilot study on

the rotating chair. Thus it may be concluded that there is no evidence for a physiological up-down asymmetry in vertical eye movements in man, that could explain the differences between the responses found during acceleration and deceleration of the centrifuge in the present study.

Matsuo and Cohen (1984) observed in monkeys that the otolith organs suppress velocity storage for the downbeat nystagmus in the upright position; the relationship of optokinetic afternystagmus to head position suggests that the otoliths exert a conditioning effect on the discharge time constant of the central integrator. This seems to be quite in agreement with the proposed indirect otolithic pathway in Fig. 7, where the otolith output controls the feedback gain element h in the central integrator.

#### 6 IMPLICATIONS FOR THE AVIATOR IN HIGH PERFORMANCE AIRCRAFT

The findings on vertical nystagmus during a coordinated high G turn have practical significance: Baloh et al. (1986) reported that vertical nystagmus is difficult to suppress by visual fixation, especially in the downbeat direction. In our study, suppression of nystagmus by fixation was only partial during G onset and offset. The degree of suppression might be even less when the visual target is not as clearly defined, e.g. during visual scanning of instruments, or during a visual search task.

In high performance aircraft both the G onset rate and the level of  $3G_z$  used in our experiment, are often largely exceeded, which means that even stronger nystagmoid eye movements are to be expected in flight. Recent modelling of the otolith mechanics indicates that the sensitivity of the system extends over a large range of shear force, due to an increased stiffness of the gelatinous layer with continued deflection (Grant and Best, 1987).

Vestibular stimulation in a high G environment could therefore have a major impact on pilot task performance in two aspects:

(1) Incomplete suppression of nystagmus will lead to impaired visibility of instruments, and consequently to a decrement in the aviator's ability to perform those tasks where visual displays are of prime importance. Benson and Guedry (1971) described a correlation between the error in a tracking task and nystagmus spv.

In addition to the blurring effects of nystagmus, Lentz and Guedry (1982) observed an apparent deflection of instrument horizon during and after rolling maneuvers. Because the aviator is not aware of nystagmus, the tracking of an image on the retina during the slow phase could be perceived as object motion.

(2) An alteration of the dynamics of the vestibular system during G load could increase the aviator's susceptibility to spatial disorientation, and the likelihood of loss of control in flight. If, as the experimental evidence suggests, the discharge time constant of the storage integrator is prolonged by an increased G load, it could influence the perception of attitude and motion during high G maneuvers.

The vestibular perception is expected to have a higher weight in conditions where visual references are poor or even misleading, e.g. during high speed aircraft maneuvers at night.

#### 7 CONCLUSIONS

Our findings indicate that the vestibular effects of a  $3G_z$  load are manifest by an increased time constant of vertical nystagmus, and by a persistent, subject-dependent, upbeat nystagmus. An extension of the velocity storage model is proposed, with pathways from the otoliths to neural centres that generate slow phase eye movements. The otolithic contribution is composed of a direct path, and a modulation of the discharge time constant of the central integrator. The extended model is described here as the modulation model.

#### REFERENCES

- Baloh, R.W., Honrubia, V., Yee, R.D. and Jacobson, K. (1986). Vertical visual-vestibular interaction in normal human subjects. Exp. Brain Research 64, 400-406.
- Benson, A.J. and Guedry, F.E. Comparison of tracking task performance and nystagmus during sinusoidal oscillation in yaw and pitch. Aerospace Medicine, June 1971.
- Boumans, L. (1982). The human VOR, effects of adaptation, Thesis Erasmus University, Rotterdam.
- Cohen, B., Matsuo V. and Raphan, Th. (1977). Quantitative analysis of the velocity characteristics of optokinetic nystagmus and optokinetic afternystagmus. J. Physiol. 270, 321-344.
- DiZio, P., Lackner, J.R. and Evanoff, J.N. The influence of gravitoinertial force level on oculomotor and perceptual responses to Coriolis, cross coupling stimulation. Aviation, Space and Environmental Medicine, September 1987.
- Gillingham, K.K. and Wolfe, J.J. Spatial Orientation in flight. USAF School of Aerospace Medicine, Brooks AFB, TX, USA, December 1986.
- Gilson, R.D., Guedry, F.E., Hixson, W.C. and Niven, J.I. Observations on perceived changes in aircraft attitude attending head movements made in a 2-G bank and turn. Aerospace Medicine, January 1973.
- Grant, W. and Best, W. Otolith-organ mechanics: lumped parameter model and dynamic response. Aviation, Space and Environmental Medicine, October 1987.
- Hosman, R.J.A.L.S. and van der Vaart, J.C. (1978). Delft University Technical Report LR - 265.
- Lentz, J.M. and Guedry, F.E. Apparent instrument horizon deflection during and immediately following rolling maneuvers. Aviation, Space and Environmental Medicine, June 1982.
- MacFall, J.R., Riederer, S.J. and Wang, H.Z. An analysis of noise propagation in computed T2, pseudodensity, and synthetic spinecho images. Medical Physics 13 (3), May/June 1986.
- Matsuo, V., Cohen, B., Raphan, Th., de Jong, V. and Henn, V. (1979). Asymmetric velocity storage for upward and downward nystagmus. Brain Research 176, 159-164.
- Matsuo, V. and Cohen, B. (1984). Vertical optokinetic nystagmus and vestibular nystagmus in the monkey: up-down asymmetry and effects of gravity. Exp Brain Research 53, 197-216.
- Mayne, R. (1974). A systems concept of the vestibular organs. In: Handbook of sensory physiology, vol. VI, part 2, p. 530, ed. H.H. Kornhuber.
- Reulen, J.P.H., Marcus J.T., Koops, D., de Vries, F.R., Tiesinga, G., Boshuizen, K. and Bos J.E. (1988). Precise recording of eye movement: the IRIS technique Part 1. Med. & Biol. Eng. & Comput. 26, 20-26.
- Raphan, Th., Cohen, B. and Matsuo, V. A velocity-storage mechanism responsible for optokinetic nystagmus (OKN), optokinetic afternystagmus (OKAN) and vestibular nystagmus. In: Control of gaze by brain stem neurons, Developments in Neuroscience, Vol 1, edited by Baker and Berthoz, Elsevier Biomedical Press, 1977.
- Raphan, Th., Matsuo, V. and Cohen, B. (1979). Velocity Storage in the Vestibulo-ocular reflex arc. Exp. Brain Research 35, 229-248.

```
APPENDIX A Angular Velocity in the Vertical Semicircular Canal (-
pitch angular velocity) During Linear G Onset in a Coor-
dinated Turn
```

Definitions

R	- turn radius	[m]
g	- gravity acceleration = 9.8	$[m/s^2]$
с	- G onset rate	[g/s]
omega	<ul> <li>angular velocity centrifuge</li> </ul>	[rad/s]
alfa	= gondola swing angle in roll	[rad]
omegp	- angular velocity in vertical semic. canal	[rad/s]
G,,	normal G load in centrifuge gondola	$[m/s^2]$
Acf	- centripetal acceleration	$[m/s^2]$

Conditions (pascal notation)

Coordinated turn	:	G,	-	sqrt(g*g + Acf*Acf)	(1)
		Acf	-	omega*omega*R	(2)
		alfa	-	$\arccos(g/G_{\tau})$	(3)
Linear G profile	:	G,	-	g*(1+c*t)	(4)
Swing in roll	:	omegp	-	omega*sin(alfa)	(5)

Derivation

```
of omegp with R=4:
Subst. (4) and (2)
    in (1) : omega = 0.5*sqrt[sqrt{g*g*c*t*(2+c*t)}] (6)
Subst. (4)
    in (3) : alfa = arccos{1/(1+c*t)} (7)
Finally, subst. (6) and (7) in (5) yields omegp.
```

#### APPENDIX B

Model of the Otoliths, simplified (Hosman and van der Vaart, 1978)



Fig. 8a Approximate model of otolith dynamics, applied in the model calculations. The system is described by a second order model, with a deflection signal as output. Feedback terms are the viscous damping r/m and the elastic torque k/m.

- $\ddot{\mathbf{x}}$  = acceleration of the head
- m mass of otolith
- r = viscous damping coefficient
- k spring stiffness
- y displacement of the otoconia relative to the macula

Numerical values (Mayne, 1974):  $(r/m) = 1.69 [1/s]; (k/m) = 0.285 [1/s^2].$ 

The notation  $\ddot{x}$  as input is used for compatibility with existing models in literature, although in the present case of gravitoinertial force the input (with dimension force per unit mass) is not produced by second derivative of an x.

Model of Cupula-endolymph Dynamics, simplified (Boumans, 1982):

$$\ddot{\Theta}_{c} = \ddot{\Theta}_{h} - \frac{B}{I} \dot{\Theta}_{c} - \frac{K}{I} \Theta_{c}$$



Fig. 8b Approximate model for the cupula-endolymph system, applied in the model calculations. Input is angular velocity of the head, output is cupula deflection. Feedback terms in the second-order system are the damping torque B/I and elastic torque K/I.

- $\theta_h$  angular displacement of the head
- θ<sub>c</sub> - angular displacement of the cupula
- Ι - moment of inertia of the endolymph
- В - damping torque, determined by the viscosity of the endolymph
- K = elastic torque, determined by the stiffness of the cupula.

Numerical values:  $(B/I) = 50 [1/s]; (K/I) = 10 [1/s^2].$ 



Fig. 9 TUTSIM blockdiagram of the extended velocity storage model presented in Fig. 6. For a given  $G_z$ profile, the angular velocity of the vertical semicircular canal was calculated in advance and written to a file, which is led into the cupula dynamics by means of the "DAT" block. The corresponding  $G_z$  profile is programmed in the function generator block "FNC", and led into the otolith dynamics by activating the timer TIM.

APPENDIX C Final model in a TUTSIM diagram

APPENDIX D Programs (listings are available on request)

Name	Function
T3.SIM CENTR3.FOR	TUTSIM model listing, corresponding to Fig. 9. Calculation of centrifuge dynamics, and the angular velocity in the vertical semicircular canal. Note: Time resolution and output-format must confirm to the TUTSIM model. Format: see label 90.
FITEXP.FOR	Fitting an exponential of the form $spv = A * exp(-t/T_c)$ .
<b>READVES</b> . FOR	Calculation of nystagmus spv.

	REPORT DOCUMENTATION P	AGE		
L DEFENCE REPORT NUMBER (MOD-NL) TD 89-3367	2. RECIPIENT'S ACCESSION NUMBER	3. PERFORMING ORGANIZATION REPORT NUMBER 1ZF 1989-24		
. PROJECT/TASK/WORK UNIT NO.	5. CONTRACT NUMBER	6. REPORT DATE July 19, 1989		
732.4	A88/M/318			
7. NUMBER OF PAGES	8. NUMBER OF REFERENCES	9. TYPE OF REPORT AND DATES		
26	26 17 Fin			
D. TITLE AND SUBTITLE Influence of gravito-inertial f	orce on vestibular nystagmus in man			
1. AUTHOR(S)				
J.T. Marcus				
<ol> <li>PERFORMING ORGANIZATION NAME(S)</li> <li>TNO Institute for Perception Kampweg 5</li> <li>3769 DE SOESTERBERG</li> </ol>	AND ADDRESS(ES)			
3. SPONSORING/MONITORING AGENCY NAM	ME(S) AND ADDRESS(ES)			
TNO Division of National Defenc Koningin Marialaan 21 2595 GA DEN HAAG	e Research			
4. SUPPLEMENTARY NOTES				
15. ABSTRACT (MAXIMUM 200 WORDS, 10 The influence of high +Gz gravi investigated in a centrifuge wi acceleration to 3G was analysed the effects of increased G load in a subject-dependent persisting	44 BYTE) to-inertial force (= G load) on the ves th a freely swinging gondola. The vert , and compared with reference measureme are expressed in a prolonged time cons ng component of this nystagmus.	tibular system in man has been cal vestibular nystagmus induced by ents at 1G. Our results indicate that tant of the upbeat nystagmus, and		
5. ABSTRACT (MAXIMUM 200 WORDS, 10 The influence of high +Gz gravi investigated in a centrifuge wi acceleration to 3G was analysed the effects of increased G load in a subject-dependent persisti In an attempt to explain these is extended: angular accelerati compensatory eye movements via vestibular nuclei. This model i influencing eye movements via This influence of G load on the role in inducing spatial disorie	44 BYTE) to-inertial force (= G load) on the ves th a freely swinging gondola. The verti , and compared with reference measureme are expressed in a prolonged time cons ng component of this nystagmus. findings, a current model on the genera on stimulates the semicircular canals, a direct reflex path, as well as throug s extended with the G load as a stimulu direct path, as well as through a modu vestibular system could interfere with entation.	stibular system in man has been cal vestibular nystagmus induced by ents at 1G. Our results indicate that stant of the upbeat nystagmus, and ation of vestibular induced eye movemen which in an existing model induce slow h an integrating network in the centra is function for the otoliths, which are alating action on the central integrato in visual perception, and thereby play a		
<ul> <li>5. ABSTRACT (MAXIMUM 200 WORDS, 10         The influence of high +Gz gravi investigated in a centrifuge wi acceleration to 3G was analysed the effects of increased G load in a subject-dependent persisti In an attempt to explain these is extended: angular accelerati corpensatory eye movements via vestibular nuclei. This model i influencing eye movements via a This influence of G load on the role in inducing spatial disori     </li> <li>6. DESCRIPTORS</li> </ul>	44 BYTE) to-inertial force (= G load) on the vest th a freely swinging gondola. The verti , and compared with reference measureme are expressed in a prolonged time cons ng component of this nystagmus. findings, a current model on the genera on stimulates the semicircular canals, a direct reflex path, as well as throug s extended with the G load as a stimulu direct path, as well as through a modu vestibular system could interfere with entation.	stibular system in man has been cal vestibular nystagmus induced by ents at 1G. Our results indicate that stant of the upbeat nystagmus, and otion of vestibular induced eye movement which in an existing model induce slow of an integrating network in the central is function for the otoliths, which are clating action on the central integrator in visual perception, and thereby play a		
<ul> <li>5. ABSTRACT (MAXIMUM 200 WORDS, 10 The influence of high +Gz gravi investigated in a centrifuge wi acceleration to 3G was analysed the effects of increased G load in a subject-dependent persisti In an attempt to explain these is extended: angular accelerati corpensatory eye movements via vestibular nuclei. This model i influencing eye movements via a This influence of G load on the role in inducing spatial disori</li> <li>6. DESCRIPTORS Vestibular perception Gravity Nystagmus</li> </ul>	44 BYTE) to-inertial force (= G load) on the vest th a freely swinging gondola. The vert , and compared with reference measureme are expressed in a prolonged time cons ng component of this nystagmus. findings, a current model on the genera on stimulates the semicircular canals, a direct reflex path, as well as throug s extended with the G load as a stimulu direct path, as well as through a mode vestibular system could interfere with entation.	stibular system in man has been cal vestibular nystagmus induced by ents at 1G. Our results indicate that stant of the upbeat nystagmus, and ation of vestibular induced eye movement which in an existing model induce slow of an integrating network in the central is function for the otoliths, which are ulating action on the central integrator in visual perception, and thereby play a IDENTIFIERS		
<ul> <li>15. ABSTRACT (MAXIMUM 200 WORDS, 10 The influence of high +Gz gravi investigated in a centrifuge wi acceleration to 3G was analysed the effects of increased G load in a subject-dependent persisti In an attempt to explain these is extended: angular accelerati compensatory eye movements via vestibular nuclei. This model i influencing eye movements via a This influence of G load on the role in inducing spatial disorier  16. DESCRIPTORS  Vestibular perception  Gravity  Nystagmus </li> </ul>	44 BYTE) to-inertial force (= G load) on the vest th a freely swinging gondola. The verti , and compared with reference measureme are expressed in a prolonged time cons ng component of this nystagmus. findings, a current model on the genera on stimulates the semicircular canals, a direct reflex path, as well as throug s extended with the G load as a stimulu direct path, as well as through a modu vestibular system could interfere with entation. 17b. SECURITY CLASSIFICATION (OF PAGE)	IDENTIFIERS		
<ul> <li>15. ABSTRACT (MAXIMUM 200 WORDS, 10 The influence of high +Gz gravi investigated in a centrifuge wi acceleration to 3G was analysed the effects of increased G load in a subject-dependent persisti. In an attempt to explain these is extended: angular accelerati compensatory eye movements via vestibular nuclei. This model i influencing eye movements via a This influence of G load on the role in inducing spatial disori. </li> <li>16. DESCRIPTORS Vestibular perception Gravity Nystagmus </li> <li>17a. SECURITY CLASSIFICATION (OF REPORT) </li> <li>18. DISTRIBUTION/AVAILABILITY STATEM</li></ul>	44 BYTE) to-inertial force (= G load) on the vest th a freely swinging gondola. The verti , and compared with reference measurement are expressed in a prolonged time consist indings, a current model on the generation on stimulates the semicircular canals, a direct reflex path, as well as through s extended with the G load as a stimulu direct path, as well as through a model vestibular system could interfere with entation. 17b. SECURITY CLASSIFICATION (OF PAGE) - MENT	Itibular system in man has been cal vestibular nystagmus induced by ents at 1G. Our results indicate that stant of the upbeat nystagmus, and ation of vestibular induced eye movement which in an existing model induce slow than integrating network in the central is function for the otoliths, which are ulating action on the central integrator in visual perception, and thereby play a         IDENTIFIERS         17c. SECURITY CLASSIFICATION (OF ABSTRACT)         -         17d. SECURITY CLASSIFICATION		

## VERZENDLIJST

	1.		Hoofddirecteur van de Hoofdgroep Defensieonderzoek TNO
	2.		Directie Wetenschappelijk Onderzoek en Ontwikkeling Defensie
	2		Hoofd Wetenschappelijk Onderzoek KL
	5.	ł	Plv. Hoofd Wetenschappelijk Onderzoek KL
4	, 5.		Hoofd Wetenschappelijk Onderzoek KLu
	6	,	Hoofd Wetenschappelijk Onderzoek KM
	ο.	ſ	Plv. Hoofd Wetenschappelijk Onderzoek KM
	7.		Wnd. Directeur Militair Geneeskundige Diensten Cdre vliegerarts H.H.M. van den Biggelaar
	8.		Inspecteur Geneeskundige Dienst KL Brig.Genarts B.C. Mels
	9.		Inspecteur Geneeskundige Dienst KLu Cdre J.Th. Versteeg
	10.		Inspecteur Geneeskundige Dienst Zeemacht Cdr-arts A.J. Noordhoek
	11.		Kolvliegerarts P.I.C.J. Burgers, ALG-IGDKLu, Soesterberg
	12.		Majvliegerarts C.R. van Holten, projectbegeleider, Hengelo
	13.		Drs. J. Smit, NLRGC, Soesterberg
	14.		Drs. R. Simons, NLRGC, Soesterberg
	15.		Drs. J. Krol, NLRGC, Soesterberg
	16.		Ir. R.J.A.W. Hosman, afd. Vliegtuigbouwkunde, TU Delft
17, 18,	19.		Hoofd van het Wetensch. en Techn. Doc en Inform. Centrum voor de Krijgsmacht

.....

#### LEDEN WAARNEMINGS CONTACT COMMISSIE

- 20. Maj.Ir. W.C.M. Bouwmans
- 21. LTZAR1 F.D.J.R. Feunekes
- 22. Dr. N. Guns
- 23. Drs. C.W. Lamberts
- 24. Ir. P.H. van Overbeek
- 25. Drs. W. Pelt
- 26. Maj. dierenarts H.W. Poen
- 27. Drs. F.H.J.I. Rameckers
- 28. Prof.Ir. C. van Schooneveld
- 29. LKol.Drs. H.W. de Swart
- 30. Kol. vliegerarts B. Voorsluijs

Extra exemplaren van dit rapport kunnen worden aangevraagd door tussenkomst van de HWOs of de DWOO.