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DEVELOPMENT OF AN ELECTRO-PNEUMATIC ANTI-G VALVE FOR HIGH PERFORMANCE FIGHTER AIRCRAFT

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ABSTRACT

A new concept for an anti-G suit valve was designed and built at the Air Force Aerospace Medical Research Laboratory. The valve is designed specifically to protect aircrew from the unique physiological hazard of high onset rate, high sustained acceleration. The design is a hybridization of a conventional inertially operated valve and uses an electronically controlled solenoid to drive the anti-G suit pressure to the maximum when the level of acceleration exceeds both +2Gz and an onset rate of 2G/sec. After a .5 sec period the valve reverts to inertial operation unless the trigger criteria are fulfilled again. Relaxed tolerance of 15 human subjects was determined under high rate of onset centrifuge testing of the new valve (with and without ready pressure) versus the standard valve and a high flow ready pressure valve. The new concept provides a 1G improvement over the standard valve, and a 0.5 G improvement over the high flow ready pressure valve. On the basis of published data taken under similar conditions, the new valve appears to provide a 0.5 G improvement over all electronic servo valves. Pilot acceptance of this rapid acting concept has been favorable.

INTRODUCTION

Current high performance fighter aircraft are routinely exceeding man's +Gz acceleration tolerance. In response to this problem, research and development efforts over the past decade have produced two types of improved anti-G valves. One type is a version of the conventional standard mechanical spring/mass valve (Burton, 1979). The other type is based on the principles of electronic servo feedback systems. Two such valves have been independently proposed by Air Force (Van Patten, 1973) and Navy (Crosbie, 1983) researchers. Recently, a new anti-G valve concept combining the advantages of both the mechanical and the electronic approaches has been developed and tested at the Air Force Aerospace Medical Research Laboratory at Wright Patterson Air Force Base. This paper describes the concept of that valve and the centrifuge test results.

METHODS AND MATERIALS

Valve Description

The concept is based upon a hybridization of the inertially operated valve. The modifications to the valve consist of the addition of a new top housing containing an aerospace quality solenoid and associated bang-bang servo electronics. At +Gz levels below +2Gz <u>and</u> at onset rates of less than 2G/sec., the valve acts as a High Flow, Ready Pressure Alar Corp. valve. This feature allows standard maneuvers without invoking the rapid acting high G protection mode of the valve.

In high onset G maneuvering, arbitrarily defined as involving onset rates greater than 2G/sec., the valve's high onset rate protection mode is activated when both trigger criteria, +Gz greater than +2Gz <u>and</u> rate of onset greater than 2G/sec., are met. Because of the well known noise problems associated with electronic differentiation, we have used a novel comparator circuit to discriminate rate of onset.

When the two trigger criteria have been met, the electronic circuit fires the solenoid for a period of 1.5 sec. In prototype testing, the time period was selectable from 0.5 to 3.0 sec. During initial tests it was found that driving the valve full open for a period of 1.5 sec. filled the suit to the maximum permitted pressure. This inflation rate equates to an equivalent onset rate of about 6G/sec. After the suit fills to full pressure, the valve reverts to the standard inertial mode of operation. Thereafter, the valve provides proportional open loop control of the suit pressure unless the two trigger criteria are still being fulfilled. In that case, the valve fires again under control of the bang-bang servo (BBS). By operating in this hybrid fashion, the valve immediately provides the highest possible level of protection presently permitted by Mil-V-9370D in terms of G-suit pressure. This valve provides optimized pilot protection during the period of greatest physiological vulnerability; the first few seconds of a high rate of onset acceleration epoch (Henry, 1944).

Valve Testing Procedure

The AFAMRL three-axis man-rated centrifuge, the Dynamic Environment Simulator (DES), was used to evaluate the new valve's G-protection capability. Since the nominal onset rate of the normally configured DES is about 1G/sec., the gondola seat installation was rearranged so that the subject faced the center of rotation. In this configuration, the main arm is accelerated to the necessary angular velocity with the subject exposed to acceleration in the +Gx axis. All anti-G valves tested were mounted so that the sensitive axis of the valve was essentially normal to the +Gx vector, but tilted into the vector slightly (about 13 degrees) to avoid the "stiction" effects which occur with side loading on mechanical valves.

The seat used has a ninety degree seatback/seatpan angle and, initially, the seatback is normal to the Gx vector during the run-up. When the main arm velocity reaches the desired value the gondola is gimbaled, under computer control, approximately 77 degrees toward the center of rotation in order to develop the high onset rate. An onset rate of 3G/sec. was used since it is generally agreed in the acceleration community that this rate is more than sufficient to provoke the physiological symptoms of interest.

The method just described ordinarily does not adversely affect the subjects. During an earlier research project that used this method, one subject (of 20) experienced transitory motion sickness. That subject had no further problems during subsequent exposures. One reason for the lack of adverse side-effects is that the subject's head is situated coaxially with the gondola axis of rotation, thereby limiting the movement of the subject's vestibular system with respect to the two spin vectors. Our experience with this technique, and the lack of adverse side-effects parallels that of earlier work (Von Beckh, 1972).

One possible problem with this technique is the effect of +Gx acceleration on the subjects prior to the +Gz epoch. Previous work has shown that +Gx acceleration has a relatively minor effect on cardiac hemodynamics (Wood, 1961). Subjects exposed to +5Gx for ten minutes had no systematic change in stroke index (the volume of blood pumped with each beat of the heart, adjusted for the subject's body surface area), or peripheral vascular resistance, and only a minor increase (20%) in cardiac output (the volume of blood pumped by the heart each minute). In the first minute of the 5Gx epoch, heart rate increased by 35 beats per minute and blood pressure increased only by 17mm Hg (Wood, 1961). Since stroke index and cardiac output did not dramatically change, a major blood shift probably does not occur with +Gx acceleration. Thus, prior to the transition to +Gz, and commencement of blood pooling in the lower body, a relative baseline (1Gz) blood distribution existed. The physiological effects of +Gx acceleration using this technique were present for each test condition. Accordingly, if a comparison between test conditions is made, the +Gx effects on the individual cancel out.

Subjects and Equipment

Fifteen active-duty Air Force men, ages ranging from 24 to 40 (mean 28 yrs.) participated in this study after giving informed consent.

During both the indoctrination and data runs the subjects were equipped with the CSU-13/P anti-G suit. During the indoctrination runs, the subjects were provided with the production Alar anti-G valve in all but two cases. Those two subjects were provided with the experimental valve in order to check out the suit inflation time. Physiological monitoring in all runs consisted of the standard three lead ECG array, and EMG monitoring of the left arm in order to assess straining. All subjects were instructed to position the left hand on the lap, with the palm up, to reduce the impulse to brace against the seat.

Monitoring G Tolerance

Subjects monitored the status of their peripheral vision using a peripheral light bar after the method of Cohen (1981). In this technique, the subject tracks his progressive loss of peripheral vision by positioning the lights with a side-arm force stick controller. When the subject's visual angle subtended less than 60 degrees, the subject was judged to have experienced peripheral light loss (PLL), and the centrifuge automatically shut down. The subjects were also monitored visually for evidence of straining with a television camera.

Experimental Procedures

Indoctrination runs were commenced at +2Gz using the 3G/sec. onset rate. If a subject was able to tolerate one epoch without experiencing PLL, the next acceleration exposure was at a 0.5G higher level. Each of the runs had a plateau duration of 15 sec.; a value chosen as reasonable based upon information gathered from operational F-16 pilots. The data runs differed from the indoctrination runs only in that data runs were commenced at +3Gz, and in that any one of the four different valves were used. During the data runs, the exposures were continued (with at least a one minute pause at baseline 1.4Gz) until the subject reached the peripheral light loss (PLL) endpoint. The experimental runs were conducted in a double blind fashion; neither the subject, the investigator, nor the centrifuge operating crew knew which valve was being used prior to a data run. This was done to remove subject and investigator bias from the experiment. The four valves were presented to the subjects in a randomized manner.

Calculation of G Tolerance

The method was a weighted average based upon the level at which the endpoint PLL was reached, and the time of endurance at that level (Crosbie, 1983). The time of endurance was divided by 15 (seconds) and the resulting factor multiplied by 0.5G. The product was added to the preceding level that the subject had sustained for the full 15 seconds and that sum was defined as the endpoint PLL acceleration tolerance.

G(tol.) = (time at plateau/15)(0.5G) + previous peak G

Data Collection

Data taken during the runs consisted of continuous digital collection of +Gz values measured at the valve site, time at plateau, heart rate, and peripheral vision angle, and valve pressure, as well as continuous strip chart recordings of these variables.

Statistical Methods

Two analyses of variance were performed with Gz tolerance and time at plateau prior to PLL as the dependent variables. In both cases the factors used were subject and valve. F-tests showed a significant difference among the valves for Gz tolerance ($F(3,36)=25.64$, $p=.0001$) and for time at plateau prior to PLL ($F(3,36)=4.78$, $p=.0066$). A Bonferrani means separation, using an experiment wise error level of .05, was performed to determine which of tha valves were significantly different with respect to Fz tolerance or time at plateau prior to PLL.

Results

Two of the original 15 subjects' data was excluded because these subjects experienced PLL during the first plateau using the standard valve. The levels of +Gz tolerance provided by the various anti-G valves are shown in Table 1. The high flow ready pressure valve utilizing ready pressure increased relaxed G tolerance approximately 0.5G protection over the standard valve. The BBSV conferred an additional 0.5G protection over the HFRP valve, and 1.0G over the standard valve. In the BBS valve, ready pressure did not provide any statistically significant effect on tolerance. The mean times to reach PLL during the G plateaus are shown in Table 2.

Table 1

Valve

	Standard	HFRP with RP	B-BS with RP	B-BS without RP
Mean GZ tol. ± S.D. of subjects	4.08 ± .48	4.62 ± .52	5.11 ± .50	5.14 ± .54

Means connected by the same line are not significantly different.

Table 2

Valve

	HFRP with RP	Standard	B-BS with RP	B-BS without RP
Mean time ± S.D. of subjects	6.05 ± 2.06	6.50 ± 1.41	8.25 ± 2.14	9.16 ± 3.59

Means connected by the same line are not significantly different.

Discussion

The BBS valve provided an additional 1 Gz protection to relaxed subjects over the standard valve. The high flow ready pressure valve provided a 0.5 G increase in G-protection which is identical to the 0.5 G increase reported by Crosbie (1983) using an electronic servo valve. It is interesting to speculate on the BBS valve's mechanism of improved protection. Both the high flow and electronic servo valves are based on the principle that more rapid g-suit inflation will result in more G-protection. The BBS valve extends this principle by pressurizing the anti-G suit at a rate that exceeds, for example, the onset rate of 6G/sec. developed by the F-16. Burton (1973) found that inflating the anti-G suit just prior to the commencement of an acceleration epoch increased tolerance by 0.5G when using a standard anti-G valve and stated that application of suit pressure to the body as rapidly as possible is essential for optimum protection at high G onset rates. The BBS valve apparently provides superior protection by inflating the suit so rapidly that it outpaces the acceleration onset rate. The result is an additional 0.5G of protection.

In terms of ease of production the BBS valve has a number of advantages. The mechanical portion of the design is composed of components already flight qualified, and no further mechanical development is required. Second, this is an inexpensive design, particularly so in comparison to the high cost of all electronic servo valves ($6000 to $15000 in prototype form). Third, as in the case of all electronic valves, the BBSV concept also embodies the capability to incorporate altered suit pressure versus G profiles to meet the needs of future fighter aircraft. Fourth, the device incorporates/retains an inherently "fail operational" feature. In the event of circuit or power disruption in this design, the pilot would continue to benefit from the protection provided by a conventional inertially operated high flow valve. This is a feature that has not been incorporated in any electronic servo valve to date. To do so would result in even higher costs for an already costly concept.

Finally, from the life cycle cost (LCC) standpoint, this valve has the very attractive advantage of permitting every standard and high flow valve to be eventually retrofitted and converted to a BBSV. Except for the older standard valves, the only required modifications to the valve mechanisms would be a simple machining operation on the press-to-test slug assembly.

Inevitably, pilot acceptance is always an issue when a new concept is introduced into the life support equipment arena. Among the subject panel participating in the evaluation of this valve were two who were experienced fighter and test pilots. Their comments were extremely positive, noting clearer central vision at endpoint at the higher level of tolerance provided by this valve.

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